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Electronic Properties of Acetaminophen Adsorbed on 2D Clusters: A First Principles Density Functional Study

Ujjal Saikia,[a, b] Nabanita Saikia,*[a] Kevin Waters,[a] Ravindra Pandey,*[a] and Munima Bora Sahariah[b]

The interaction of acetaminophen (N-acetyl-para-aminophenol), a prominent analgesic and antipyretic, with 2D clusters was investigated using density functional theory with inclusion of van der Waals dispersion correction. The implicit solvation model with three different solvents; water, ethanol and carbon tetrachloride were utilized to observe the trends in binding energy as a function of solvent polarity. The calculated results demonstrate that interactions are not solely dependent on solvent polarity, but inherent properties of the 2D clusters drive the nature of the interaction; i.e. physisorbed states were favored for graphene, boron nitride (BN), and phosphorene, whereas a chemisorbed state is preferred for silicene. Analysis of the frontier orbitals and density of states (DOS) show that the acetaminophen functionalization induces mid-gap energy states in BN. Chemisorbed acetaminophen on silicene induces a *2p* core level shift in silicon. The calculated results provide atomistic insights on the nature of interactions of acetaminophen with the new class of 2D materials beyond graphene for potential sensing applications.

Introduction

Acetaminophen (N-acetyl-para-aminophenol), commonly known as paracetamol, is a widely prescribed analgesic and antipyretic medication administered for medium to severe pains related to backache, headache, arthritis and postoperative pains.[1–4] For acetylsalicylic acid (aspirin) sensitive patients, acetaminophen is a preferred therapeutic.[5] Long term administration or overdose of acetaminophen can cause serious health issues which includes fatal hepatoxicity, nephrotoxicity, liver disorders, skin rashes, and inflammation of the pancreas.[4,7–8] The other cause of concern is the reported acetaminophen contamination in drinking water. A recent survey on pharmaceuticals in drinking water stressed the requirement of extensive research on health hazards associated with long-term exposure to low concentrations of pharmaceuticals and/or combined effects of mixtures of pharmaceuticals.[9] Therefore, development of a viable method for the detection of acetaminophen in drinking water has become important to meet environment standards.

Graphene, a single atomic thick 2D carbon allotrope has been foreseen as a versatile material for several applications,[10–13] with significant potential as a sensor for hazardous gases,[14–16] organic molecules,[17] bio- and chemotherapeutic drug molecules.[18] Recently, it has been shown that electrochemical detection of acetaminophen molecule is possible with electrochemically reduced graphene (ERG) deposited onto a glassy carbon electrode (GCE).[19]

Given the substantial applications of graphene, interest has been shifted to a new class of 2D nanomaterials like boron nitride (BN), silicene, and phosphorene. The sensing properties of BN has been reported using experimental and theoretical methods to investigate its applications as molecular sensors.[20–24] Likewise, silicene, a buckled honeycombed structure of Si atoms is currently being considered as sensors for gas molecules like CO, NH_3, NO, NO_2.[25,26] Unlike graphene which is stabilized by sp^2 hybridization along the carbon lattice, silicene is stabilized by a mixed sp^2-sp^3 hybridization[27,28] which leads to the puckered morphology. Phosphorene, is an sp^3 hybridized material[29] with a highly buckled morphology which is responsible for its anisotropic electronic properties.[30,31]

The novel aspects of 2D materials beyond graphene have provided the motivation to investigate the potential application of a few experimentally synthesized 2D materials as sensing materials for acetaminophen. In a recent study, the electronic and optical response of graphene based 2D nanomaterials towards functionalization of pyrazinamide (PZA)[32] was investigated which highlighted the inherent properties of the nanomaterials governing the nature and extent of interaction.

In the present study, density functional theory (DFT) calculations were performed to investigate the response of graphene, boron nitride (BN), silicene and phosphorene towards acetaminophen in a solvated phase. The solvent phase is represented by the continuum model using the following solvents; water (H_2O), ethanol (C_2H_5OH) and carbon tetrachlor-

[a] *U. Saikia, Dr. N. Saikia, K. Waters, Prof. R. Pandey*
Department of Physics
Michigan Technological University
Houghton, MI 49931-1295, USA
Tel: 906–487-2086
Fax: 906–487-2933
E-mail: nsaikia@mtu.edu
pandey@mtu.edu

[b] *U. Saikia, Dr. M. B. Sahariah*
Institute of Advanced Study in Science and Technology
Guwahati 781035, Assam, India

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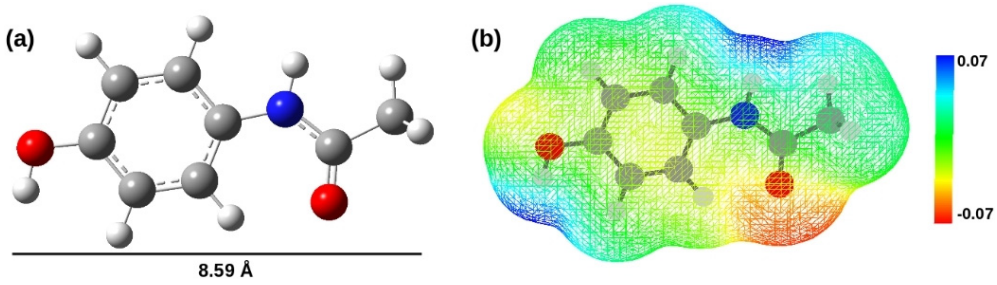


Figure 1. Acetaminophen in the solvent phase: (a) the equilibrium configuration, (b) ESP isosurface. Red region corresponds to the higher electron density and blue corresponds to region of lower electron density.

ide (CCl_4). A detailed analysis of the calculated results is performed to achieve atomistic details on interactions governing the formation of conjugated complexes and feasibility of 2D clusters in the detection of acetaminophen for the next generation devices at nanoscale level. In Section 2, the computational method is briefly described. The results are discussed in Section 3 and the summary is given in Section 4.

Computational Method

First principles calculations within the framework of DFT have been performed using the Gaussian09 software suite.[33] The exchange correlation functional form was treated within the Generalized Gradient Approximation (GGA) using the Perdew, Burke, and Ernzerhof (PBE) functional[34] and the 6–31G (d,p) basis set.[35] The convergence criteria for the geometry optimization was set to 10^{-4} eV/Å for the maximum force and for the RMS it was 10^{-4} eV/Å. The convergence criteria in the RMS density matrix and total energy were 10^{-8} and 10^{-6} eV, respectively.

Grimme's dispersion correction term (D2) is included to describe the weakly bound noncovalent interactions.[36,37] Although the Grimme's D2 is not the sole method for accounting the noncovalent van der Waals interactions in weakly bound complexes, it does provide comparable results at a reasonable computational cost compared to other computationally expensive methods like CCSD(T).[38,39] The Grimme's D2 method does provide a reasonable understanding on energetics of interaction of the conjugated complexes and demonstrate trends in the nature and extent of adsorption of acetaminophen on 2D clusters.

The equilibrium configurations of the conjugated complexes were found by extensive conformational search of the potential energy surface representing interaction of acetaminophen with the 2D materials. Considering that the solvent polarity may play a critical role in conjugated complexes dominated by noncovalent interactions e.g. electrostatic, π-π, and vdW interactions, the polarizable continuum model (PCM)[40] was employed. In principle, a detailed comparison of implicit vs. explicit solvent models would be a better route to effectively mimic the solvent environment towards the intermolecular interactions. However, in the study, we have considered the implicit solvent description. The implicit solvent model represents a continuum (statistically averaged) media and is found to be invaluable in modeling reactivity of different solvents with differing polarity values.[41] Water, ethanol and CCl_4 were taken as the reference solvents having dielectric constant values of 78.36, 24.85 and 2.23, respectively. Note that CCl_4 is a non-polar solvent whereas water is polar solvents which can participate in H-bonding in conjugated complexes.

Molecular adsorption on 2D materials and surfaces typically employ periodic calculations replicating the characteristics of an infinite surface. However, cluster models can successfully describe properties and energetics of interactions that are localized in nature like adsorption[42,43] and core level shifts.[44] The focus of the study is on investigating the localized structural and electronic properties towards the adsorption of a acetaminophen molecule, and not on transport or conductance measurements. Graphene, phosphorene, silicene and BN were modeled by a 120 atoms cluster with the edge atoms passivated by hydrogen atoms. In this regard, cluster size is an important consideration for the accuracy and reliability of cluster model. The convergence of total energy and an electronic property like HOMO-LUMO energy gap as a function of cluster size were investigated previously.[32] The energies are converged with increase in the cluster size and as expected, the HOMO-LUMO energy gap decreases with increase in cluster size. Although a cluster model with two neighboring regions around the central hexagon (i.e. $X_{54}H_{18}$ cluster) was proven to be effective for proton transport in 2D clusters,[45] a larger $X_{96}H_{24}$ cluster was considered to further reduce edge effects influencing the interaction in the conjugated complexes.

Results and Discussion

Acetaminophen

Acetaminophen is a planar molecule[46,47] which can be visualized by two substituent groups to the aromatic benzene ring (a) -OH group, (b) -$NHCOCH_3$ group as shown in Figure 1a. The presence of -$NHCOCH_3$ group renders torsional flexibility along the benzene ring upon conjugation with 2D clusters. The calculated structural parameters are listed in the Supporting Information, Table S1. The overall charge distribution within acetaminophen can be visualized by the electrostatic potential (ESP) map.[48] Figure 1b shows higher electron density associated with the electron donating oxygen atom of the -C=O group (electrophile) in -$NHCOCH_3$ fragment of the molecule.

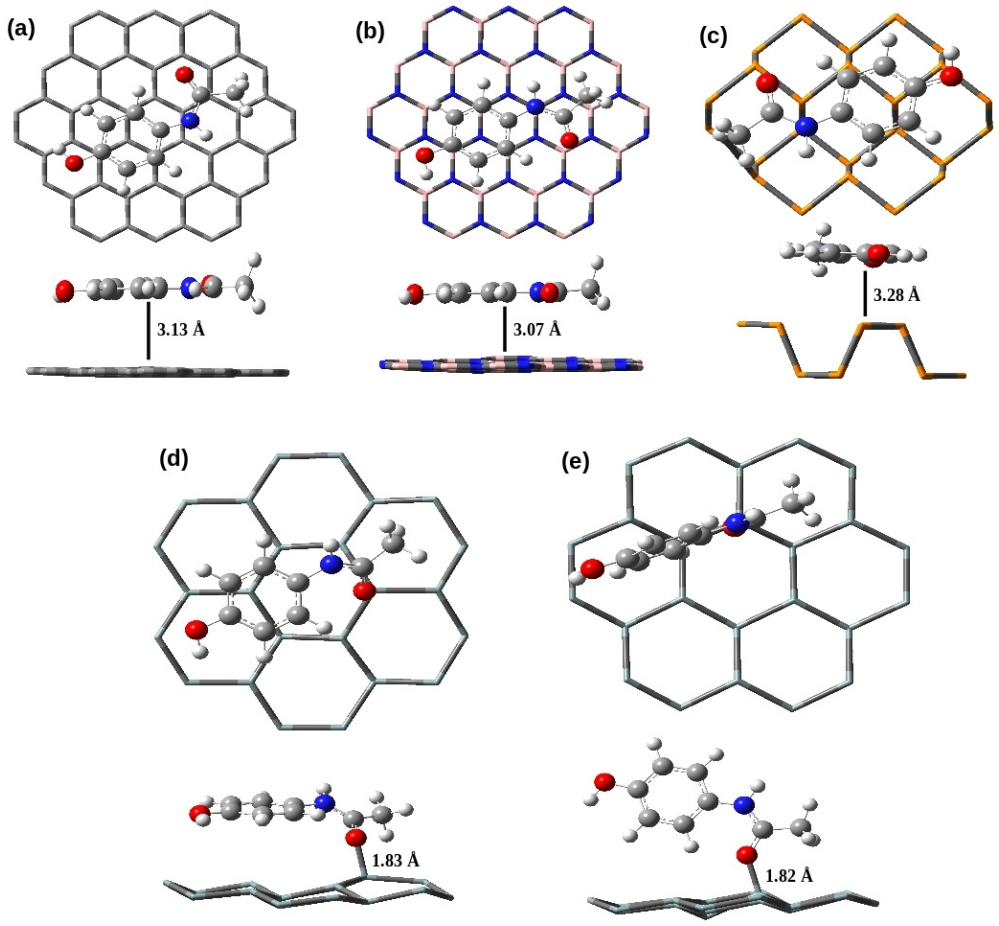


Figure 2. Fragment of the cluster depicting equilibrium configurations of the acetaminophen/2D conjugate in water solvent phase: (a) graphene, (b) BN, (c) phosphorene and (d) silicene at parallel and (e) silicene at perpendicular orientations. The interplanar distance is defined as the minimum distance between the two atoms belonging to the acetaminophen molecule and the cluster.

2D materials

The calculated equilibrium configurations of finite clusters representing graphene, BN, phosphorene and silicene are taken from our previous study,[32] and are displayed in Figure S2 of the Supporting Information. Graphene and BN are planar honeycombed structures and the average bond length in graphene and BN is 1.42 and 1.45 Å, respectively (Supporting Information, Table S2). Phosphorene reveals a quadrangular pyramid structure with a dihedral puckering angle of ~78–79° and buckling distance of ~2.2 Å. Silicene has a low buckled honeycomb structure with Si–Si bond length of 2.28 Å, buckling distance of 0.51 Å, and a dihedral puckering angle of 39°. The calculated HOMO-LUMO gap is 1.34, 4.50, 1.52 and 0.53 eV for graphene, BN, phosphorene and silicene, respectively. In the periodic 2D models, graphene and silicene are semi-metallic while BN is a wide band gap insulator and phosphorene is a semiconducting material. In our finite cluster model, these exists the HOMO-LUMO energy gap for graphene and silicene (Table S2 of Supporting Information), and the calculated energy gaps have a strong correlation on the shape of clusters model considered for an equivalent number of carbon/silicon atoms. The pristine 2D clusters have zero dipole moment values.

Acetaminophen conjugated 2D materials

Three distinct adsorption sites within the 2D clusters are considered: bridge, hollow and top sites for adsorption of acetaminophen based on the alignment of the aromatic rings. The choice of interacting sites is guided by previous studies of PZA conjugated 2D clusters[32] and aromatic molecule adsorption on graphene.[49,50] Apart from the parallel configuration which facilitates maximum π-orbital overlap with the 2D clusters, perpendicular orientations of adsorption were also investigated. The calculated equilibrium configurations of acetaminophen/2D conjugates are depicted in Figure 2.

The binding energy ($\triangle E_b$) for the preferred conformation of acetaminophen conjugated $X_{96}H_{24}$ clusters were calculated using the following:

$$\Delta E_b = E_{acetaminophen/cluster} - (E_{acetaminophen} + E_{cluster}) \quad (1)$$

where, $E_{acetaminophen/cluster}$ is total energy of the complex, $E_{acetaminophen}$ and $E_{cluster}$ are total energies of the acetaminophen molecule and the pristine 2D cluster, respectively.

Table 1 lists the interplanar distance, binding energy values and dipole moments of the acetaminophen conjugated clusters calculated in solvent phase. Acetaminophen is physisorbed on graphene and BN at an interplanar distance of 3.13 and 3.07 Å,

Table 1. Calculated binding energy ($\triangle E_b$), interplanar distance, Mulliken charge transfer from acetaminophen to the cluster, and dipole moment of the conjugated complexes in solvent phase (|| = parallel and ⊥ = perpendicular configuration for the silicene/acetaminophen conjugate).

System	$\triangle E_b$ (eV)	Interplanar distance (Å)	Charge transfer (|e|)	Dipole Moment (Debye)
Graphene	-0.87	3.13	0.01	2.5
BN	-1.10	3.07	0.06	3.2
Phosphorene	-0.91	3.28	0.27	6.1
Silicene ||	-0.94	1.83	0.57	16.2
⊥	-1.12	1.82	0.48	15.7

respectively. The Top site was favored for graphene, and the N-top site was preferred for BN clusters. Likewise, the Top site was preferred for phosphorene at an interplanar distance of 3.28 Å. Both the parallel (||) and perpendicular (⊥) orientations of acetaminophen were favored on silicene because of the formation of a stable Si–O polar covalent bond with a bond length of 1.83 Å. Of the studied 2D clusters, a prominent localized perturbation within the relaxed geometry was observed for silicene, induced by the chemisorbed acetaminophen that leads to enhanced buckling along the bonding site.

In general, the nature of bonding and hybridization within graphene, BN, silicene and phosphorene determine the degree of stability towards the functionalization of acetaminophen. Acetaminophen is physisorbed on graphene with a binding energy of −0.87 eV and negligible charge transfer. Phosphorene is sp^3 hybridized unlike graphene, and acetaminophen prefers physisorption with a net charge transfer of 0.3e. BN being ionic in nature due to the electronegativity difference between boron and nitrogen atoms prefers physisorption of acetaminophen with a binding energy of −1.10 eV. Since acetaminophen is a polar molecule, rendered from the -OH and -$NHCOCH_3$ functional groups, the interaction with BN yields a higher binding energy compared to graphene and phosphorene suggesting the influence of inherent electronic property of 2D materials towards the functionalization. Of the studied 2D clusters, prominent localized perturbation within the relaxed geometry was observed for silicene. The binding energy of the acetaminophen/silicene conjugate at the perpendicular (parallel) orientation is calculated to be −1.12 eV (-0.94 eV) at an interacting distance of 1.82 Å (1.83 Å).

The chemisorbed configurations of acetaminophen/silicene can be correlated to the inherent electronic property of the pristine silicene cluster. Unlike graphene which exhibits sp^2 hybridization, the bonding in silicene exhibits a mix of sp^2-sp^3 hybridization.[51,52] Silicene prefers chemisorption which can be explained by the lack of stable sp^2 bonds.[53,54] The Silicon (Si) atoms have a larger atomic radius compared to carbon atoms of graphene and the π bonds in silicene (formed by the coupling of adjacent p_z orbitals) are much weaker than graphene. Adsorption of organic/gas molecules induces the local Si atoms in silicene to complete sp^3 hybridization with the formation of stable chemisorbed complexes. The acetaminophen adsorbed Si–Si bond is pulled outward from the silicene sheet with an increase in bond length from 2.28 Å to 2.33 Å. This structural deformation attributes to the change in the hybridization of Si atoms from sp^2/sp^3 to sp^3.

In the ESP isosurface of acetaminophen depicted in Figure 1b, the O atom attached to the CH_3 group is the dominant reactive site that drives the interaction upon conjugation with silicene and the delocalized O atom (with two lone pair of electrons) constitutes the polar covalent bond with the Si atom of silicene. Mulliken charge analysis demonstrates a net charge transfer of ~ 0.5e for the acetaminophen/silicene conjugate which can be associated to the increased dipole moment of ~ 16D and negligible charge transfer in acetaminophen/graphene and acetaminophen/BN complexes (see Table 1).

NBO analysis of acetaminophen/silicene complex

In the chemisorbed complexes of acetaminophen/silicene, the natural bond orbital (NBO) analysis serves as a valuable tool to obtain insights on the intermolecular orbital overlap by charge transfer and interactions within the complex. In NBO, the electronic wavefunction is expressed in terms of occupied Lewis (corresponding to σ and π bonding or lone pair) and non-Lewis (acceptors, antibonding or unoccupied) orbitals. Interactions result in the loss of occupancy from a localized Lewis orbital to an unoccupied orbital leading to donor-acceptor interactions.55 The magnitude can be obtained from the Fock Matrix and the associated stabilization energy ($E^{(2)}$) between a donor (i) → acceptor (j) as follows:

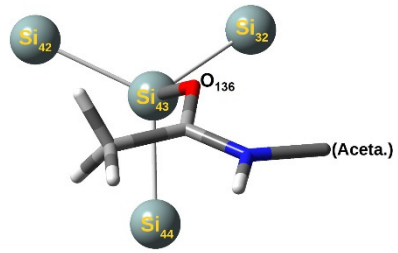
$$E^{(2)} = \Delta E_{ij} = q_i \frac{F(i,j)^2}{\varepsilon_i - \varepsilon_j} \quad (2)$$

where, q_i is the orbital occupancy of the donor, $F(i,j)$ is the off diagonal Fock matrix element, and ε_i and ε_j are the diagonal elements.[56] The largest value of stabilization energy ($E^{(2)}$), suggest electron transfer from donor → acceptor, and the extent of delocalization of electron density within the system. The delocalization effects can be identified from the off-diagonal elements of Fock matrix.[57]

To substantiate the nature of the bonds within the acetaminophen/silicene conjugate, the NBO analysis was considered. The results suggest formation of a polar (Si_{43}-O_{136}) covalent bond. The natural orbital occupancies and hybrids of Si–Si σ bonds for the first neighboring atoms of Si atom (i.e. Si_{43}) interacting with the O atom are listed in Table 2. The σ (Si_{32}- Si_{43}), bond is formed from $sp^{2.4}$ hybridized (29% s and 71% p) atomic orbitals. The σ (Si_{42}-Si_{43}) bond is formed from $sp^{2.3}$ hybrid (30% s, 70% p) and σ(Si_{43}-Si_{44}) bond is from $sp^{2.1}$ hybrid (32% s and 68% p) atomic orbitals, respectively. The highest occupancies are calculated for the σ-bonded Si atoms (occupancy = 1.95e) and the lone pair of electrons in O_{136} atom of acetaminophen (occupancy = 1.68e). The Si_{43} atom involved in the polar covalent bond with the O_{136} atom has the lowest occupancy of 0.46e.

Table 3 lists the second order perturbation energies between the donor → acceptor orbitals of acetaminophen/silicene complex. The intermolecular interaction and overall

Table 2. Occupancy of the natural bond orbitals (NBOs) and hybrids in the silicene/acetaminophen conjugate for the case of | | orientation. Here, σ, LP, and LP* represent bonding, lone pair bonding and lone pair antibonding NBO orbitals, respectively.



NBOs	Occupancy	Hybrid	AO (%)
$\sigma(Si_{32}$ - $Si_{43})$	Si_{43} - 1.95	$sp^{2.4}$	s (29) p (71) d (0.2)
$\sigma(Si_{42}$ - $Si_{43})$	Si_{43} - 1.95	$sp^{2.3}$	s (30) p (70) d (0.2)
$\sigma(Si_{43}$ - $Si_{44})$	Si_{43} - 1.95	$sp^{2.1}$	s (32) p (68) d (0.3)
LP^*Si_{43}	Si_{43} - 0.46	$sp^{26.1}$	s (4) p (96) d (0.1)
LP O_{136}	O_{136}- 1.68	$sp^{16.3}$	s (6) p (94)

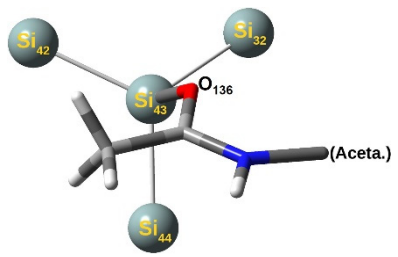
Table 3. Second order perturbation theory analysis of the stabilization energies ($E^{(2)}$, eV) for the acetaminophen/silicene complex for the case of | | orientation. The terms $E_{(j)}$, $E_{(i)}$, and F(i, j) are the diagonal elements and the off-diagonal elements between the *i* and *j* NBO orbitals. Here, σ, σ*, LP and LP* represents bonding, antibonding, lone pair bonding and lone pair antibonding NBO orbitals.

Donor →	Acceptor	$E^{(2)}$ (eV)	$E_{(j)}$-$E_{(i)}$ (a.u.)	F(i, j) (a.u.)
LP O_{136}	LP^*Si_{43}	3.19	0.4	0.17
LP O_{136}	LP^*Si_{43}	4.05	0.3	0.15
σ C_{131} - O_{136}	LP^*Si_{43}	0.71	0.9	0.12
σ Si_{32} -Si_{43}	LP^*Si_{43}	0.05	0.4	0.02
σ Si_{42} -Si_{43}	LP^*Si_{43}	0.03	0.4	0.02
σ Si_{43} -Si_{44}	LP^*Si_{43}	0.04	0.4	0.02
LP^* Si_{43}	σ*C_{131} - O_{136}	0.01	0.4	0.06
LP O_{136}	σ*Si_{32} - Si_{43}	0.07	0.6	0.03
LP O_{136}	σ*Si_{42} - Si_{43}	0.03	0.6	0.02
LP O_{136}	σ*Si_{42} - Si_{43}	0.0	0.5	0.01
LP O_{136}	σ*Si_{43} - Si_{44}	0.20	0.5	0.04

stabilization to the complex is formed by the orbital overlap between the lone pairs on the O atom (donor) and antibonding orbitals of the Si atom (acceptor) involved in the Si–O bond with corresponding stabilization energies of 3.19 and 4.05 eV, respectively. The stabilization energy of 0.71 eV was calculated for the interaction of the donor C_{131}-O_{136} σ-bond to the lone pair antibonding orbital of the Si_{43} atom (Table 3).

The trends in NBO analysis are further substantiated from the Natural Population Analysis (NPA) for the acetaminophen/silicene complex and the calculated NPA atomic charges and orbital population are provided in Table 4. The natural population for the selected atoms resemble trends calculated from the Mulliken population analysis, with a positive NPA charge on the Si_{43} atom bonded to O_{163} of acetaminophen. The first neighbor Si atoms, i.e. Si_{44}, Si_{32} and Si_{44}, have negative charges and demonstrate partial sp^3 character. The high *p*-character in O_{136} (natural charge of −0.75e) facilitates the interaction with Si_{43} of silicene with delocalization of electronic charge density along the binding site.

Table 4. The natural charges and electronic configurations of Si atoms located near the interacting site in the acetaminophen/silicene complex.



Atom	Natural Charge |e|	Electronic Configuration
Si_{32}	-0.05	3 s (1.2) 3p (2.8)
Si_{42}	-0.10	3 s (1.2) 3p (2.9)
Si_{43}	**0.50**	3 s (1.1) 3p (2.4)
Si_{44}	-0.12	3 s (1.2) 3p (2.9)
O_{136}	**-0.75**	2 s (1.7) 2p (5.1)

Electronic Properties

Functionalization of graphene, silicene and phosphorene with acetaminophen does not modify the HOMO-LUMO energy gaps pf the pristine 2D clusters. This is not the case with the pristine BN which has an energy gap of 4.50 eV (Table S2 of Supporting Information). Functionalization of acetaminophen introduces mid-gap states thereby lowering the energy gap to 3.63 eV due to the states associated with acetaminophen. The mid-gap states is further ascertained from the density of states (DOS) analysis and frontier orbital isosurface as discussed in the subsequent sections.

The DOS of acetaminophen, graphene, BN, acetaminophen/graphene and acetaminophen/BN conjugates are depicted in Figure 3. For the acetaminophen/graphene conjugate, the physisorbed acetaminophen does not affect the band gap of the pristine graphene (Figure 3a). The presence of mid-gap states around −4.75 eV for BN (Figure 3b) is associated with acetaminophen.

Figure 4 displays the frontier molecular orbitals of acetaminophen/graphene and acetaminophen/BN complexes. For acetaminophen/graphene, the frontier molecular orbitals ranging from HOMO-1 to LUMO+2 are associated with the delocalized basal surface of graphene (Figure 4b). In the acetaminophen/BN conjugate, HOMO is contributed solely by the orbitals from acetaminophen, whereas contributions from both BN and acetaminophen constitute the LUMO and LUMO+1 orbitals (Figure 4d). The contribution towards LUMO+2 is from BN and acetaminophen. In the DOS of BN complex, the mid-gap state can be attributed to the HOMO

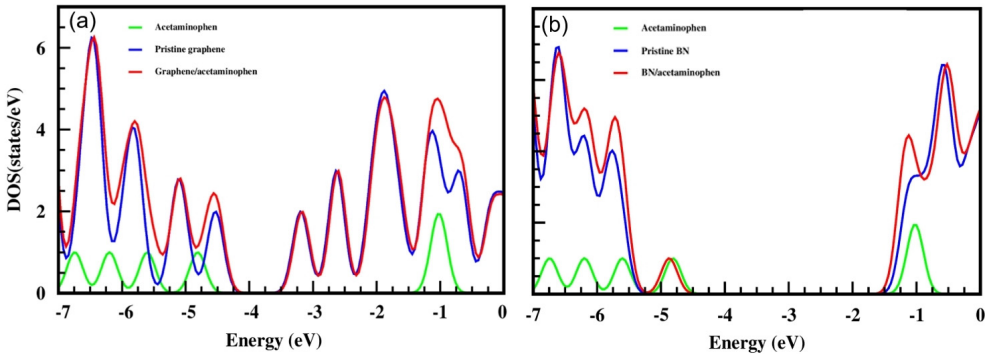


Figure 3. Density of States (DOS) of acetaminophen (green), graphene/BN (blue) and graphene/BN-acetaminophen conjugate (red) in (a) acetaminophen/graphene, (b) acetaminophen/BN complexes.

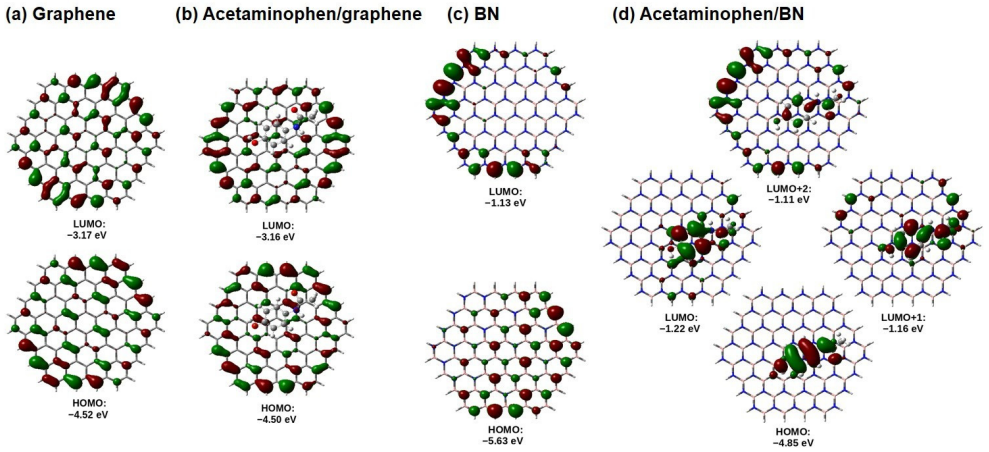


Figure 4. Frontier molecular orbitals of (a) graphene, (b) acetaminophen/graphene, (c) BN and (d) acetaminophen/BN conjugated complexes.

state of the acetaminophen molecule.

Frontier orbital isosurface from HOMO-2 to LUMO + 2 states in graphene, phosphorene, acetaminophen/graphene and acetaminophen/phosphorene complexes are provided in the Supporting Information, Figures S4 and S6. In the case of phosphorene, HOMO is associated with the acetaminophen, HOMO-1 and HOMO-2 are localized around the edges of the phosphorene sheet, whereas LUMO to LUMO + 2 states are contributed by the inner phosphorene buckled honeycombs (Supporting Information, Figure S6). The frontier orbitals of acetaminophen/silicene is shown in Figure 5. For both the parallel and perpendicular orientations of adsorption (Figure 5b and c), except for the HOMO which are contributions along the Si–O bond and first neighboring Si atoms, the LUMO to LUMO + 2 orbitals represent states contributed mainly by silicene. The frontier orbitals from HOMO-2 to LUMO + 2 of pristine silicene and acetaminophen/silicene conjugate is provided in Supporting Information, Figure S7.

A comparison of the molecular orbital energy levels in pristine 2D clusters and the corresponding functionalized conjugates are shown in Figure 6. Negligible influence on the energy states for graphene is found. However, HOMO levels shift upward for BN, phosphorene and silicene complexes showing contributions from acetaminophen. Overall, the physisorbed acetaminophen does not perturb the electronic properties of graphene and phosphorene. This is not true for the BN complex due to appearance of mid-gap states associated with physisorbed acetaminophen. In the silicene complexes, chemisorbed acetaminophen perturbs the electronic structure of silicene at the covalent bonding site. In the following section, we quantify the predicted perturbation in acetaminophen/silicene complex by analysis of the core level shifts which can be measured by X-ray Photoelectron Spectroscopy.

Core level shift in acetaminophen/silicene conjugate

Core level spectroscopy can serve as an instrumental method to investigate dynamics of electron transfer around an atomic site, which is initiated by adsorption of an X-ray photon to eject a core electron.[58,59] The core level shifts are highly sensitive to the chemical environment of an atom, and can provide valuable information on the bonding in materials,[60,61] and serve as a good indication towards sensing application in silicene conjugates. For chemically bound complexes of silicene, understanding the core level shifts can reveal perturbations in the materials upon functionalization.

The calculated core level shift in both the parallel and perpendicular configurations of the chemisorbed acetaminophen is listed in Table 5. Pristine silicene has a *2p* core energy of −94.74 eV. For the *2p* orbital involved in the formation of Si–O polar covalent bond, the core level shifts to a lower energy of −95.51 (-95.42) eV for || (⊥) configuration of adsorption. The calculated shifts in energies upon functionalization are −0.77 (-0.68) eV for the || (⊥) configuration. On the

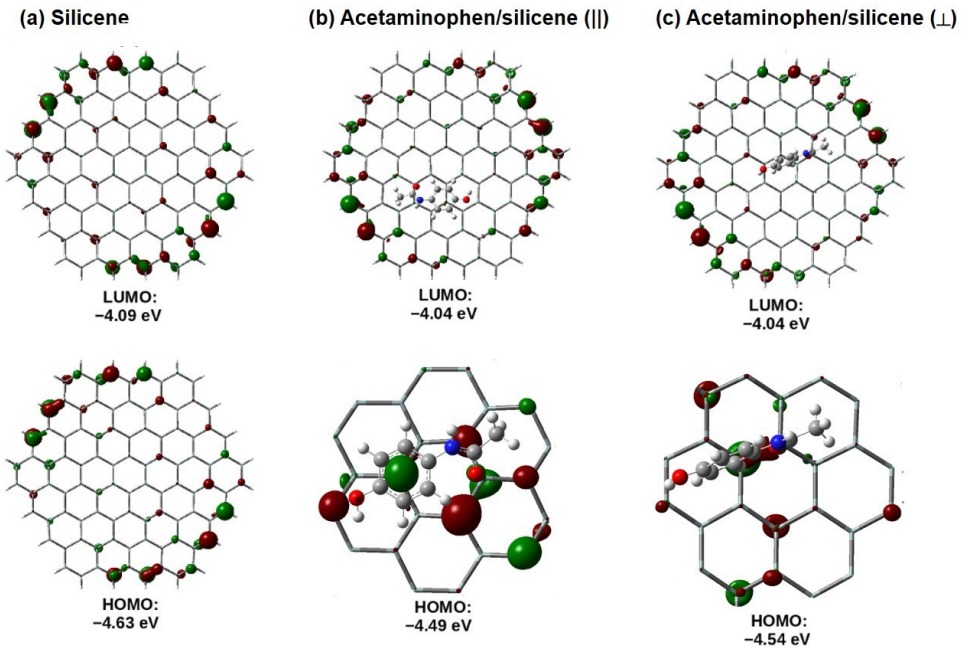


Figure 5. Frontier molecular orbitals of (a) silicene, acetaminophen/silicene conjugated complexes at (b) parallel and (c) perpendicular orientations of adsorption.

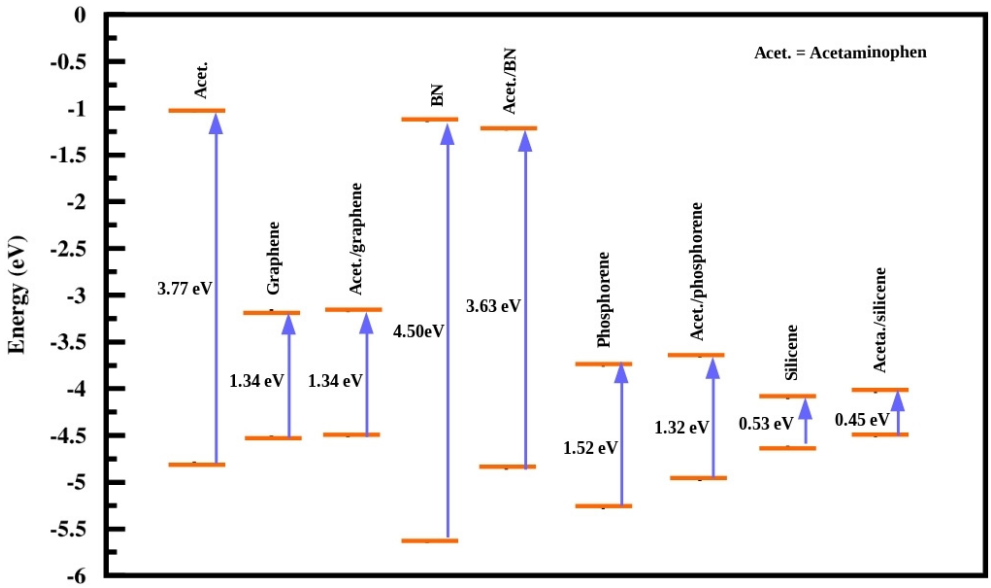
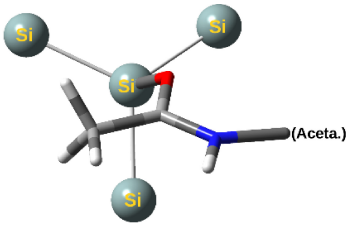


Figure 6. The Orbital energy diagram corresponding to the HOMO and the LUMO states for acetaminophen and acetaminophen conjugated 2D complexes.

Table 5. The Core level shift of pristine silicene and acetaminophen/silicene conjugate.

Orbital	Silicene sheet	Silicene/acetaminophen conjugate Configuration	Energy (eV)	Energy difference (eV)	
		||	-95.51	-0.77	
		⊥	-95.42	-0.68	
2p	-94.74				

other hand, the *2p* level of first neighbor Si atoms shifts to a higher energy of −94.37 eV. This is because, the Si atom involved in Si–O bond has a net positive charge of 0.32e (0.25e) for the || (⊥) configuration (see Supporting Information, Table S4). The net negative charge of 0.57e (0.48e) is distributed on the neighboring Si atoms. Therefore, the *2p* states experience less Coulomb repulsion and shifts to a lower bind-

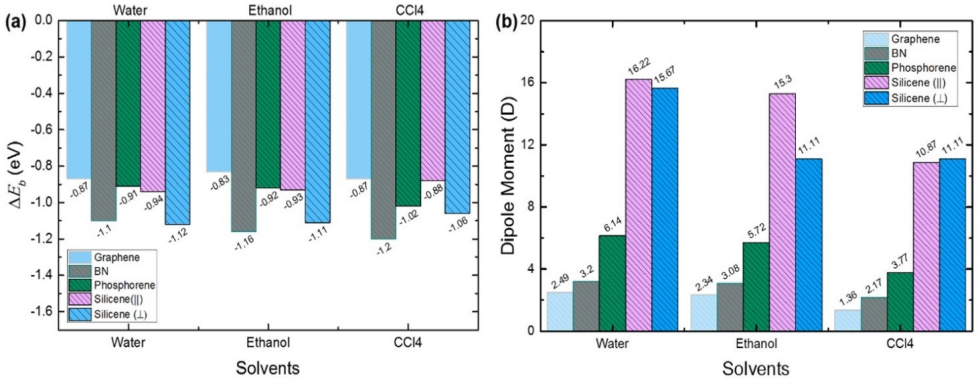


Figure 7. Variation in (a) binding energy (b) dipole moment for the conjugates of acetaminophen/2D cluster in presence of water, ethanol and CCl_4.

ing energy value, while *2p* states of neighboring Si atoms experience higher valence electron repulsion and shifts to higher binding energy values (Table 5). Note that the Si atom involved in Si–O bond has a comparatively smaller valence electron population (with a natural charge of +0.50e).

Effect of solvent on acetaminophen/2D materials

In general, solvent polarity modifies the energetics of interaction and electronic properties of the functionalized 2D complexes. This is illustrated in Figure 7 for the acetaminophen conjugated complexes in water, ethanol and CCl_4. The trend in binding energies are different for physisorbed complexes; binding energy for BN and phosphorene follows the order: CCl_4 > ethanol > water, while for graphene conjugates it is, water ≈ CCl_4 > ethanol. In the chemisorbed silicene conjugates, the interaction strength follows the order: water > ethanol > CCl_4. The calculated values of the dipole moment can be used to understand the order of interaction strength in conjugated complexes. For example, a higher dipole moment value in the acetaminophen/silicene facilitates enhanced interaction in water solvent media followed by ethanol and CCl_4. On the other hand, a lower dipole moment in acetaminophen/graphene complex facilitates higher interaction strength in non-polar CCl_4 over the polar solvents.

Conclusions

First principles (DFT–D2) calculations have been performed to investigate the interaction in acetaminophen with finite clusters of graphene, BN, phosphorene and silicene. Considering that the properties of acetaminophen does play an important role in driving the energetics of interaction, we also find that the response is dependent on inherent electronic properties of 2D materials. Silicene favors chemisorption with strong localized buckling within the sheet like that reported previously for the PZA molecule, whereas the other 2D materials favor physisorption. We find that physisorption of acetaminophen in graphene, BN and phosphorene is associated with negligible charge transfer from acetaminophen to the clusters. On the other hand, silicene prefers to interact with acetaminophen in both $\parallel$ and $\perp$ configurations with a charge transfer of ~0.5e. Functionalization of the 2D clusters does not significantly modify the energy gap of graphene and phosphorene, but it introduces a mid-gap state in BN. Calculations using the implicit solvation model show trends in binding energies as a function of the solvent polarity, which are mainly governed by the dipole moments of the conjugated complexes.

The NBO analysis for acetaminophen/silicene conjugates suggest the stabilization through formation of a polar (Si_{43}-O_{136}) covalent bond. The nature of the intermolecular interaction in the complex is governed by the orbital overlap between the lone pairs on the O atom (donor) and antibonding orbitals of the Si atom (acceptor) involved in the Si–O bond. Chemisorption of acetaminophen on silicene leads to the perturbation in the chemical environment along the binding site which was quantified by calculations of the XPS *2p* core level shifts. The core level shifts can be measured experimentally and can facilitate detailed understanding on the sensing applications and assist the theoretical findings. For the physisorbed complexes of acetaminophen on graphene, BN and phosphorene, core level shifts are negligible. For the acetaminophen/silicene complex, which favors chemisorption, it might serve as a signature towards detecting shifts in the core energy states within silicene.

The calculated results hold promise and potential for future experimental research in the molecular sensing, especially in the treatment of drinking water, wherein the new class of 2D materials can be fabricated as molecular sieves for the uptake of water borne drug contaminants. The reported results are in line with the first theoretical (DFT–D2) study from our group on the structure, electronic and optical response of 2D clusters as selective materials in molecular adsorption of functional biomolecules.

Supporting Information Summary

The supporting information consists of: discussion on basis set superposition error (BSSE); Figure S1: optimized geometry of acetaminophen; Table S1: optimized parameters of acetaminophen; Figure S2: equilibrium configurations of pristine 2D clusters of graphene, BN, phosphorene and silicene; Table S2: point group symmetry, equilibrium bond length (*d*) and HOMO-LUMO gap of the 2D clusters; Table S3: interplanar distance and

binding energies of acetaminophen/2D conjugates in gas phase; Figure S3: DOS of acetaminophen functionalized graphene, phosphorene and silicene conjugates; Figures S4-S7: frontier molecular orbitals of graphene, BN, phosphorene and silicene conjugated complexes with acetaminophen; Table S4: the Mulliken charge analysis of Si atoms in the vicinity of Si–O interaction site for both parallel (| |) and perpendicular (⊥) configurations of adsorption.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords: Acetaminophen · Core level shifts · Density functional theory · Density of States · Electronic properties · 2D materials

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