TẠP CHÍ KHOA HỌC
TRƯỜNG ĐẠI HỌC QUY NHƠN

Nghiên cứu lý thuyết về cấu trúc, độ bền và tương tác của các phân tử ampicillin và amoxicillin trên bề mặt anatase-TiO_2 (101)

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TÓM TẮT

Sử dụng các tính toán phiếm hàm mật độ, chúng tôi đã khảo sát sự hấp phụ các phân tử ampicillin và amoxicillin trên bề mặt anatase-TiO_2 (101). Mô hình tuần hoàn và sóng phẳng đã được áp dụng trong tất cả các tính toán. Kết quả chỉ ra rằng các quá trình này được đánh giá là các quá trình hấp phụ hóa học với năng lượng khoảng -31 kcal.mol^{-1}. Độ bền của các cấu hình được đóng góp đáng kể bởi các tương tác hút tĩnh điện Ti ··· O và các liên kết hydro kiểu O/N/C-H··· O. Sự tồn tại và vai trò của các tương tác bề mặt trong việc làm bền phức được phân tích chi tiết dựa vào cách tiếp cận hóa học lượng tử. Kết quả cho thấy khả năng hấp phụ của ampicillin trên bề mặt anatase mạnh hơn so với amoxicillin. Đáng chú ý, sự xắp xếp theo chiều ngang với diện tích bề mặt tiếp xúc lớn được diễn ra ưu tiên trong việc kết dính các phân tử kháng sinh này lên bề mặt anatase.

Từ khóa: *Anatase, kháng sinh, tính toán DFT, bề mặt vật liệu.*

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Theoretical study of geometry, stability and interaction in configurations of ampicillin and amoxicillin molecules on the surface of anatase-TiO_2 (101)

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ABSTRACT

By using density functional theory calculations, we examined the adsorption of ampicillin (AP) and amoxicillin (AX) molecules on anatase-TiO_2 (101) surface (a-TiO_2). The periodic slab model and plane wave method were applied in all calculations. Results indicate that these processes are evaluated as chemical adsorptions with associated energies of -31 kcal.mol^{-1}. Stability of configurations is significantly contributed by Ti···O electrostatic interactions and O/N/C-H ··· O hydrogen bonds. Existence and role of surface interactions in complex stabilization are analyzed in detail based on quantum chemical approaches. As a consequence, the adsorption capacity of AP on the a-TiO_2 is slightly stronger than that of AX. Remarkably, the horizontal arrangement along with large surface area occurred favorably in adhesion of these antibiotics on the a-TiO_2.

Keywords: *Anatase, antibiotics, DFT calculations, material surface.*

1. INTRODUCTION

In many decades, TiO_2 has been of the important semiconductor materials applied in fields such as energy, health, food technologies.[1,2] TiO_2 was used extensively in photocatalytic, adsorption, decomposition of pollutants due to its considerable surface properties. The investigations on surface properties of TiO_2 using experimental technologies and theoretical simulations were interested by scientists.[3] TiO_2 existed in three common phases including anatase, rutile and brookite.[2-4] Among phases of TiO_2, the anatase has high photocatalytic activity and is observed widely. Furthermore, the (101) surface of anatase is the most stable one and frequently form.[4] The adsorption of organic molecules on TiO_2 surfaces has been previously reported.[3-7] As a consequence, TiO_2 can be used as potential material for efficient adsorption of organic compounds.

In addition, the nature of intermolecular interactions on TiO_2 surfaces and their role to the stability of complexes have not been paid much attention by scientists.[8,9] This understanding is of importance for further evaluation of molecules adsorption, especially for photocalytic reactions occurred onto TiO_2 surfaces in order to form simple products such as CO_2, H_2O.[2,3,5,7] Besides, interactions between antibiotics used widely such as ampicillin (AP), amoxicillin (AX) and material surfaces have not been much paid attention. Our previous investigations indicated that the adsorption of these molecules on vermiculite or adsorption of enrofloxacine molecule on rutile-

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TiO_2 are strong chemisorptions.[10,11] However, the insight into adsorptive interactions of antibiotics on anatase-TiO_2 surfaces has been still not mentioned fully yet. Noticeably, quantum chemistry computations are emerging as useful tools in understanding surface phenomena in nature.[12] Hence, in the present work, we use DFT caculations to investigate the adsorptive interaction of AP, AX molecules on anatase-TiO_2 (101) surface. Moreover, this work is performed with an aim to have a convenient evaluation on adsorption capacity of AP, AX on an anatase surface and to also serve in finding efficient material for removal of pollutants.

2. COMPUTATIONAL METHODS

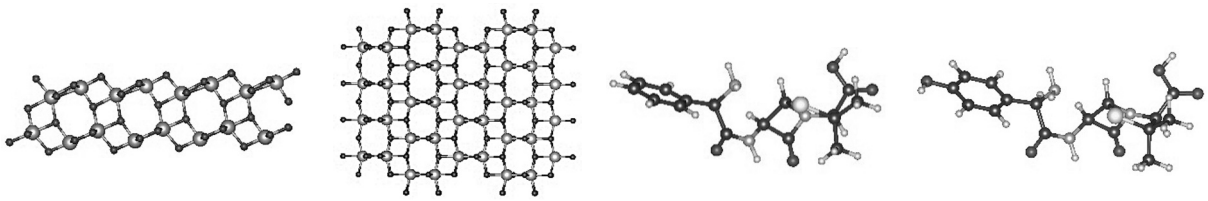
The structures of anatase surface and molecules and configurations are optimized by using the VASP program.[13] The (101) surface of anatase is designed with 4 x 5 x 2 supercell of primitive cell which has been characterized by following dimension parameters: a = 15.22 Å; b = 20.87 Å; c = 30.01 Å. The cutoff energy and grid k-points are considered at 500 eV and 4 x 3 x 1 Gamma points, respectively. The atomic positions are optimized until a force value is smaller than 0.01 eV. The energy convergence is set up at 1.10^{-6} eV. The Perdew-Burke-Ernzernhof (PBE) functional in conjugation with generalized gradient approximation (GGA) is used in all computations.[14] The adsorption energy (E_{ads}) is calculated by expression: $E_{ads} = E_{comp} - E_{surf} - E_{mole}$ where E_{comp}, E_{surf} and E_{mole} are energy values of optimized configurations, surface and molecules, respectively.

In order to have an insight into the existence and role of the intermolecular interactions upon the adsorption process, quantum chemistry analyses based on Atoms In Molecular (AIM) and Natural Bonds Orbitals (NBO) approaches are carried out at the B3LYP/6-31+G(d,p) level for first-layered structures of the most configurations. The transfers of total electron density (EDT) following interactions formation are also considered for these structures. These calculations are performed by using Gaussian 09, AIM2000 and NBO 5.G programs.[15-17]

3. RESULTS AND DISCUSSION

3.1. Stable structures

The optimized geometries of anatase-TiO_2 (101) surface (denoted by a-TiO_2) and AP, AX molecules are displayed in Figure 1. Some characterized parameters including bond length, angle are compared to experimental data and theoretical results in previous studies.[3-7] As a matter of fact, the calculated parameters in this work are in a good agreement with previous reports in which the changes of bond lengths and angles are *ca.* 0.01-0.05 Å and 1-3°, respectively. The ground states of configurations for adsorption of AP and AX molecules onto a-TiO_2 are illustrated in Figure 2. These structures are denoted by **APi** and **AXi** (i = 1-4), following different arrangements of AP, AX molecules on surface to have a convenient look. The **AX4** is found out only for AX system due to interaction of –OH group attached to benzene ring as compared to AP system. As shown in Figure 2, the stable configurations obtained for two systems have similar geometrical structures, particularly for **AP1** and **AX1**, **AP2** and **AX2**, **AP3** and **AX3**. Besides, the distances of intermolecular contacts and changes of bond lengths, angles are given in Table 1 upon complexation.



a-TiO_2 (left: Front-view; right: Top-view) Ampicillin (AP) Amoxicillin (AX)

Figure 1. Optimized structures of a-TiO_2 and AP, AX molecules

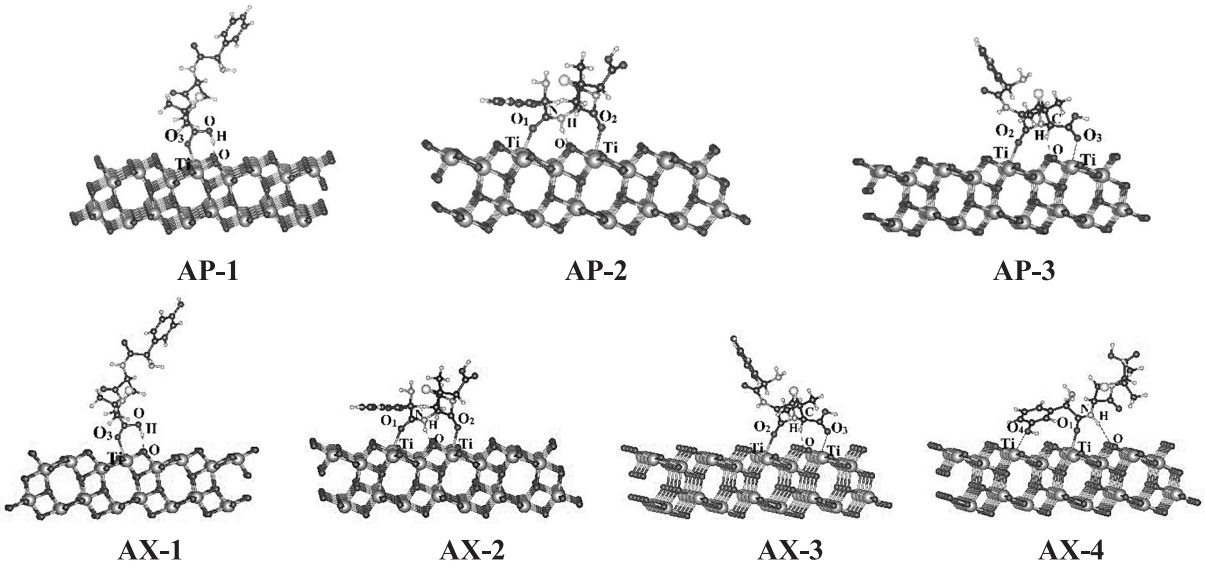


Figure 2. The optimized configurations of AP, AX adsorbed on a-TiO_2 (101) *(C, H, O, N, S, Ti atoms are displayed by grey, white, red, small cyan, yellow, cyan colors, respectively)*

Table 1. Some characteristic parameters of the stable configurations

	d(Ti···O)	d(H···O)	a(CO···Ti)	a(O/N/C-H···O)	Δr(C=O)	Δr(X-H)	Δr(Ti-O)**
AP1	2.16[3]	1.49	131.7	164.1	0.04	0.07	0.02 – 0.06
AP2	2.13[1]/2.28[2]	1.64	153.3[1]/135.0	161.9	0.04/0.02	0.03	0.01 – 0.03
AP3	2.22[2]/2.39[3]	1.86	163.2/130.8[3]	143.8	0.01/0.01	0.00	-0.02 – 0.01
AX1	2.19[3]	1.52	131.9	164.2	0.04	0.06	0.00 – 0.07
AX2	2.11[1]/2.30[2]	1.66	153.6[1]/135.5	161.7	0.03/0.02	0.03	-0.00 – 0.04
AX3	2.26[2]/2.42[3]	1.89	163.8/130.3[3]	142.1	0.01/0.01	0.00	-0.03 – 0.02
AX4	2.16[1]/2.43[4]	2.28/2.26*	151.1/125.9[4]	160.0/160.2*	0.02/0.02[4]	0.01/0.01*	0.02 – 0.03

*[1,2,3,4]-for O atoms as shown in Fig.2; *-for O-H···O; **-for O atoms at bridging sites; a-angle (°); d-distance (Å)*

As presented in Table 1, the distances of Ti···O and O/N/C-H···O contacts are in range of 2.11 to 2.43 Å and 1.49 to 2.28 Å, respectively. These values are smaller than the total of van der Waals radii of atoms involved in contacts including Ti and O (3.82 Å), O and H (2.72 Å), C and O (3.22 Å) atoms. Besides, the angles of C-O···Ti and O/N/C-H···O are corresponding to values of 125.9-163.8° and 142.1-164.2°, consistent with binding angles of C=O interactions or hydrogen bonds.[18] Therefore, it can be suggested that the Ti···O and O/N/C-H···O intermolecular interactions are formed following complexation. Also, the geometrical changes for surface and molecules are quite small in comparison with their initial structures. The change of Ti-O, C=O, X-H bonds is *ca.* 0.07 Å, 0.04 Å and 0.07 Å, respectively. The AP, AX molecules tend to arrange in horizontal sequence onto a-TiO_2 to form various intermolecular contacts, similarly to previous studies.[10,11]

3.2. Adsorption energy

In order to evaluate the strength of interactions and the capacity of adsorption of AP, AX on a-TiO_2, the adsorption energies are considered and tabulated in Table 2.

Table 2. Adsorption energy (E_{ads}, kcal.mol^{-1}) of stable configurations

i	1	2	3	4
AP-i	-22.9	-31.1	-18.6	
AX-i	-21.0	-29.3	-17.7	-25.5

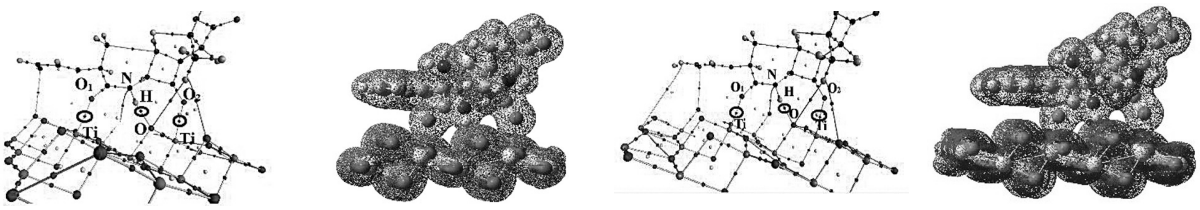
The calculated energy values in Table 2 for AP and AX systems range from -17.7 to -31.1 kcal.mol^{-1}. The strength of adhesion of AP, AX on a-TiO_2 is comparable to that of enrofloxacin on rutile-TiO_2 (110) surface.[10] Accordingly, these processes are evaluated as chemical adsorptions.[19] Moreover, the ability of adsorption of these molecules on TiO_2 surfaces is twice weaker than that on vermiculite[11] because of the smaller adsorption energy. This is understood by the significant contributions of electrostatic interactions between Mg^{2+} cation sites on vermiculite and O atoms in >C=O groups of molecules.[11]

In addition, the stability of configurations in this work is contributed by both Ti···O attractive interactions and O/N/C-H···O hydrogen bonds as displayed in Figure 2. The contributions of two Ti···O intermolecular contacts of >C=O groups and one N-H···O hydrogen bond lead to the considerable stability of **AP2**, **AX2** in comparison to the rest of configurations for AP, AX systems. In case of **AX4**, one Ti···O interaction is formed by Ti_{5f} site and O in –OH group. As given in Table 2, **AX4** is slightly less stable than **AX2** of 4 kcal.mol^{-1}. This result is due to the proton affinity (PA) at B3LYP/6-31++G(d,p) level and charge density at O atoms in C=O group (PAs are in range of 200-216 kcal.mol^{-1}) are higher than that in –OH group (PA is *ca.* 185 kcal.mol^{-1})[11], leading to the fact that Ti···O (C=O) becomes more stable than Ti···O (OH). Besides, the difference of E_{ads} values for **AP2** and **AX2** is small *ca.* 2 kcal.mol^{-1}. The approximation of PA and deprotonation enthalpy (DPE) values at O atoms and N-H bond in AP and AX molecules as analyzed in previous report makes the equally stable interactions in these configurations. In general, the adsorption capacity of AP and AX onto a-TiO_2 is slightly different.

On the other hand, one Ti···O and one O-H···O contacts (**AP1**, **AX1**) or two Ti···O and one C-H···O contacts (**AP3**, **AX3**) have an important role to their stability. The adsorption energy increases in the order of **AP2** < **AP1** < **AP3** and **AX2** < **AX4** < **AX1** < **AX3** for AP, AX systems, respectively. This is understood by basing on the ability of forming stable hydrogen bonds in configurations. The strength of hydrogen bonds increases in going from C-H···O to N-H···O and finally to O-H···O as estimated in *ref.11*. Following this report, the significant contribution of O-H···O hydrogen bonds leads to the more stable configurations of **AP1** and **AX1** as compared to **AP3**, **AX3**, respectively. In summary, the stability of obtained configurations depends on the arrangement of molecules on surface to form stable interactions, and resulted by significant contribution of Ti···O electrostatic interactions and addition of O/N-H···O hydrogen bonds.

3.3. AIM and NBO analyses

To gain an insight into existence and role of adhesive interactions, we perform topology analysis for the first layer of **AP2**, **AX2** most stable structures as displayed in Figure 3. The electron density transfers between molecules and surface are investigated further to confirm the existence of intermolecular contacts. Some characteristic parameters are gathered in Table 3.



AP2 **AX2**

Figure 3. The topological geometries of the first-layered structures for AP2 and AX2

Table 3. The topological analysis (ρ(r), electron density; $\nabla^2(\rho(r))$, Laplacian of electron density; H(r), total of electron density energy; all in au) and electron density transfers (EDT, e), hyper-conjugation energy (E^2, kcal.mol^{-1}) for the first-layered structures

	BCPs	ρ(r)	$\nabla^2(\rho(r))$	H(r)	EDT	Transfers	E^2
AP-2	O_1···Ti	0.056	0.325	0.004	0.116	π(C=O)/LP(O) → LP*(Ti)/σ*(Ti-O)	23.6
	O_2···Ti	0.039	0.204	0.004		π(C=O)/LP(O) → LP*(Ti)/σ*(Ti-O)	16.9
	N-H···O	0.052	0.153	-0.008		LP(O) → σ*(N-H)	22.6
AX-2	O_1···Ti	0.058	0.340	0.003	0.102	π(C=O)/LP(O) → LP*(Ti)/σ*(Ti-O)	22.6
	O_2···Ti	0.037	0.194	0.004		π(C=O)/LP(O) → LP*(Ti)/σ*(Ti-O)	17.0
	N-H···O	0.050	0.147	-0.007		LP(O) → σ*(N-H)	19.3

The calculated results imply that the Ti···O and N-H···O intermolecular contacts exist. The electron density (ρ(r)) and Laplacian of electron density ($\nabla^2(\rho(r))$) values at Ti···O BCPs range from 0.037 to 0.058 au and from 0.194 to 0.340 au, respectively. Similarly, the ρ(r) and $\nabla^2(\rho(r))$ at N-H···O BCPs correspond to 0.050-0.052 au and 0.147-0.153 au. All these values are within the region of ρ(r) and $\nabla^2(\rho(r))$ for noncovalent interactions.[16] Therefore, the Ti···O and N-H···O are regarded as noncovalent interactions and hydrogen bonds, respectively. The H(r) values at BCPs of N-H···O contacts are slightly negative, indicating that these interactions have a small part of covalency in nature. Besides, the stability of **AP2**, **AX2** is additionally contributed by O···C weak interactions with the small ρ(r) of 0.01 au. The ρ(r) values at Ti···O and N-H···O BCPs in **AP2** and **AX2** are mostly approximate, therefore, strength of interactions in these configurations is nearly equal. As a result, the stability of **AP2** and **AX2** is considered to be approximate.

Furthermore, the formation of adsorptive interactions is clarified by electron density transfers from molecules to surface and vice versa. As given in Table 3, the EDT is small positive, of 0.1 e due to the prominent transfers from molecules to surface. The existence of Ti···O contacts is confirmed by the transfers of electron density from lone pair of O atoms (LP(O)) and bonding orbitals of C=O (π(C=O)) in molecules to unoccupied lone pair of Ti sites (LP*(Ti)) and anti-bonding orbitals of Ti-O (σ*(Ti-O)) of a-TiO_2. Similarly, the N-H···O hydrogen bonds is formed by the electron density transfers from LP(O) of surface to σ*(N-H) of molecules. These transfers of electron density are evaluated clearly by hyper-conjunction energies (E^2) (*cf. Table 3*). Accordingly, the E^2 values for formations of Ti···O and N-H···O interactions are in the range of 17-24 kcal.mol^{-1} and 19-23 kcal.mol^{-1}, respectively. Moreover, the stability of interactions is determined by electrostatic term based on charge densities at sites of molecules and surface. The high charge density at sites leads to forming the strong electrostatic interactions. Following NBO calculations, the charge densities at O, H atoms (in **AP**, **AX**) and Ti, O sites (in a-TiO_2) are in the ranges of -0.65 to -0.74 e; 0.47 to 0.48 e; 1.61 to 1.72 e; -0.97 to -0.98 e, respectively. Therefore, Ti···O interactions are stronger than N-H···O hydrogen bonds upon complexations. This result also leads to the fact that EDT values are positive values for **AP2** and **AX2**.

4. CONCLUSIONS

In the present work, we investigated the adsorption of ampicillin and amoxicillin molecules on a anatase-TiO_2 (101) surface (a-TiO_2) using density functional theory calculations. Obtained results show that the adhesion of these antibiotics on the a-TiO_2 surface is regarded as chemical adsorption. The stable configurations are contributed significantly by Ti···O electrostatic interactions along with O/N/C-H···O hydrogen

bonds. The existence and role of adsorptive interactions in the most stable configurations **AP2** and **AX2** are clarified on the basis of the electron density transfers and charge density distribution. Generally, the adsorption of ampicillin onto the a-TiO_2 surface is slightly stronger than that of amoxicillin, *ca.* 2 kcal.mol^{-1}. The arrangement of molecules on the a-TiO_2 surface tends to be preferable in a horizontal sequence and occurs on a large surface area to form stable interactions.

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