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Seungsoo Han

Stony Brook University

Hee-Joon Chun

h.jchun@cnu.ac.kr

Chungnam National University

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Molecular-Level Understanding of Polyethylene Glycol Adsorption on $\text{TiO}_2(001)$ at the Solid–Water Interfaces

Seungsoo Han^a and Hee-Joon Chun^{b,*}

^a Department of Chemistry, Stony Brook University, Stony Brook, New York 11794, United States

^b Department of Chemistry, Chungnam National University, Daejeon 34134, Republic of Korea

* Corresponding author e-mail: hjchun@cnu.ac.kr

Abstract

Polyethylene glycol (PEG) modification is widely used to improve the colloidal stability, water compatibility, and interfacial functionality of TiO_2 nanoparticles. However, predicting saturated PEG coverage at oxide/liquid-water interfaces remains challenging because PEG adsorption is controlled by a complex balance among surface binding, inter-chain packing, hydration, water displacement, and conformational entropy. In this work, we investigate the coverage-dependent adsorption thermodynamics of PEG on anatase $\text{TiO}_2(001)$ in liquid-water using density functional theory and ab initio molecular dynamics simulations. PEG-5 adsorption was examined at coverages of 0.25, 0.50, 0.75, and 1.00 monolayer (ML), and the adsorption free energy was decomposed into PEG head-group adsorption, PEG inter-chain interaction, PEG–water solvation, H_2O desorption, zero-point energy, and entropic contributions. The enthalpic stabilization is maximized at intermediate coverage, where favorable inter-chain interactions and PEG hydration are simultaneously maintained. At higher coverages, dense PEG packing weakens head-group adsorption and PEG–water solvation, accompanied by reduced PEG–water hydrogen bonding and increased entropic penalties. The differential adsorption free energy becomes positive beyond 0.50 ML, indicating that further PEG adsorption is thermodynamically unfavorable. Gaussian process regression with bootstrap resampling gives a free energy minimum near 0.51 ML, supporting a saturated PEG-5 coverage of 0.50 ML.

Keywords: polyethylene glycol; $\text{TiO}_2(001)$; solid-water interface; ab initio molecular dynamics; density functional theory; Gaussian process regression

1. Introduction

TiO₂ is one of the most important commercial oxides and has been widely used in environmentally friendly and sustainable technologies, including photocatalysis, solar cells, heterogeneous catalysis, and biomedical applications [1,2]. In many of these applications, TiO₂ nanoparticles are processed in aqueous media before being coated on target substrates or introduced into biological environments. Therefore, the preparation of highly dispersed and colloidally stable TiO₂ suspensions is essential for minimizing nanoparticle agglomeration, improving processability, and enhancing biocompatibility. A widely used strategy to stabilize TiO₂ suspensions is surface modification with macromolecular dispersants, which can provide electrostatic repulsion and/or steric hindrance between adjacent nanoparticles. Among various macromolecules, polyethylene glycol (PEG) has attracted particular attention because of its low cost, low toxicity, excellent water compatibility, and strong affinity toward oxide surfaces [3,4].

The grafted density of PEG is a key parameter that determines the physicochemical properties of TiO₂ suspensions, including colloidal stability, hydrodynamic size, mobility, and interfacial biocompatibility [5,6]. However, determining and predicting PEG surface coverage remains challenging because adsorption at solid–liquid interfaces is inherently complex and depends on the molecular organization of both the polymer and the surrounding aqueous interface. In particular, the adsorption free energy of PEG cannot be described solely by the binding strength of its anchoring group, because inter-chain interactions, solvation by liquid-water, and water displacement from the oxide surface can all contribute significantly. Therefore, an atomistic and thermodynamic understanding of PEG adsorption is required to rationally control the saturated PEG coverage on TiO₂ surfaces.

Computational approaches based on density functional theory (DFT), ab initio molecular dynamics (AIMD), and molecular-scale simulations have provided valuable insights into PEG adsorption at TiO₂/water interfaces. Previous studies have shown that PEG conformation can change from mushroom-like to brush-like structures depending on grafting density, indicating that molecular configuration and interfacial interactions are central to understanding PEG surface coverage [7-9]. Recently, we investigated brush-type PEG adsorption on anatase TiO₂(101) using a free energy framework that decomposes the adsorption process into PEG head-group adsorption, PEG inter-chain interaction, PEG–water solvation, H₂O desorption, and entropic contributions [10]. This analysis demonstrated that the saturated PEG coverage is determined by the competition between favorable adsorption/solvation interactions and unfavorable free energy penalties arising from dense interfacial packing, water displacement, and entropy loss associated with PEG conformational restriction at high surface coverage.

Although anatase TiO₂(101) is the most stable and commonly exposed facet, anatase TiO₂(001) is also of considerable interest because its distinct surface atomic structure and higher surface reactivity can lead to different interfacial adsorption behavior [11-13]. Compared with TiO₂(101) facet, TiO₂(001) exposes a more reactive surface environment, which can alter the balance between PEG head-group adsorption, inter-chain packing, water displacement, and PEG hydration. Therefore, comparing PEG adsorption thermodynamics on TiO₂(001) provides insight into how surface facet controls the saturated PEG coverage at aqueous oxide interfaces.

In this work, we investigate PEG adsorption on anatase TiO₂(001) in the presence of liquid-water using a free energy-based computational framework. The coverage-dependent enthalpic contributions are quantified using

DFT-AIMD simulations and subsequently integrated to estimate the adsorption free energy of PEG at different surface coverages. Furthermore, Gaussian process regression (GPR)-based trend analysis is employed to construct a continuous coverage-dependent adsorption free energy profile from the AIMD-derived data, enabling estimation of the thermodynamically preferred PEG coverage on the $\text{TiO}_2(001)$ /liquid-water interface [14,15].

2. Computational details

2.1. DFT and AIMD simulations

Spin-polarized density functional theory calculations were performed using the Vienna ab initio simulation package (VASP) to investigate PEG adsorption on anatase $\text{TiO}_2(001)$ [16-19]. The interactions between valence electrons and ionic cores were described using the projector augmented wave (PAW) method, and the plane-wave kinetic energy cutoff was set to 400 eV [20]. To properly account for dispersion interactions between PEG, water, and the TiO_2 surface, the vdW-DF2 exchange-correlation functional was employed [21-23]. In addition, a Hubbard U correction of 3.0 eV was applied to the Ti 3d orbitals to reduce the self-interaction error associated with localized d states [24-26]. During geometry optimization, the electronic self-consistent field convergence criterion was set to 10^{-4} eV, and the structures were relaxed until the residual force on each atom was less than 0.05 eV/Å.

The anatase TiO_2 bulk structure with lattice parameters of $a = b = 3.78$ Å and $c = 9.62$ Å was used to construct the $\text{TiO}_2(001)$ surface model [27,28]. A (2×2) surface unit cell was employed to describe coverage-dependent PEG adsorption on $\text{TiO}_2(001)$. The slab consisted of three Ti–O layers, with the middle layer fixed during structural relaxation to represent the bulk-like region. A vacuum spacing of 15 Å was introduced along the surface-normal direction to avoid artificial interactions between periodic images. Brillouin-zone integrations were carried out using a $3 \times 3 \times 1$ Monkhorst–Pack k-point mesh.

PEG adsorption on $\text{TiO}_2(001)$ was examined at different surface coverages to evaluate the coverage-dependent adsorption free energy. PEG was modeled as $\text{H}(\text{OCH}_2\text{CH}_2)_n\text{OH}$, and PEG-5 ($n = 5$) was primarily considered in the present study. Because the present study focuses on the high-grafting-density regime relevant to PEG-modified TiO_2 surfaces, brush-oriented PEG configurations were used as representative initial structures. The results should therefore be interpreted as coverage-dependent thermodynamics within the brush-type adsorption model, rather than as an exhaustive sampling of all possible PEG conformations [10]. For each coverage, PEG molecules were initially placed on the $\text{TiO}_2(001)$ surface with their molecular chains oriented perpendicular to the surface in the presence of liquid-water, and the corresponding interfacial structures were sampled using AIMD simulations.

AIMD simulations were conducted in the canonical ensemble using a Nosé–Hoover thermostat to describe the liquid-water environment at the PEG/ $\text{TiO}_2(001)$ interface [29]. The number of water molecules was chosen so that the water density in each simulation cell was close to 1.00 g/cm³. Each system was equilibrated at 298.15 K, followed by a 10 picosecond (ps) AIMD simulation with a time step of 1 femtosecond (fs). To obtain representative adsorption energetics, 10 snapshots were extracted from each AIMD trajectory at 1 ps intervals. Each sampled structure was subsequently geometry-optimized at 0 K using static DFT calculations, and the resulting energies were averaged. All calculated energies are provided in Tables S1-S4 in the Supplementary Information (SI).

2.2. GPR and bootstrap

GPR was used as an interpolation method to obtain a statistically smoothed representation of the coverage-dependent PEG* adsorption free energy within the sampled coverage range. The PEG* adsorption free energy values calculated from AIMD-sampled structures over 1–10 ps at four PEG coverages, namely 0.25, 0.50, 0.75, and 1.00 ML, were used as the dataset, resulting in a total of 40 snapshot-level free energy values. PEG coverage was used as the input variable, and the PEG* adsorption free energy was used as the output variable. The GPR model was constructed using a radial basis function (RBF) kernel, and the kernel hyperparameters were optimized during model training. The trained GPR model was then used to interpolate the adsorption free energy between the explicitly sampled PEG coverages [30].

To evaluate the uncertainty associated with the GPR interpolation, bootstrap resampling was performed. Bootstrap datasets of the same size as the original dataset were generated by random sampling with replacement for 1,000 iterations. An independent GPR model was trained for each bootstrap dataset, and the resulting distribution of interpolated adsorption free energies was used to estimate the 95% bootstrap confidence interval (CI), defined by the 2.5th and 97.5th percentiles of the interpolated free energy values [31].

3. Results and discussion

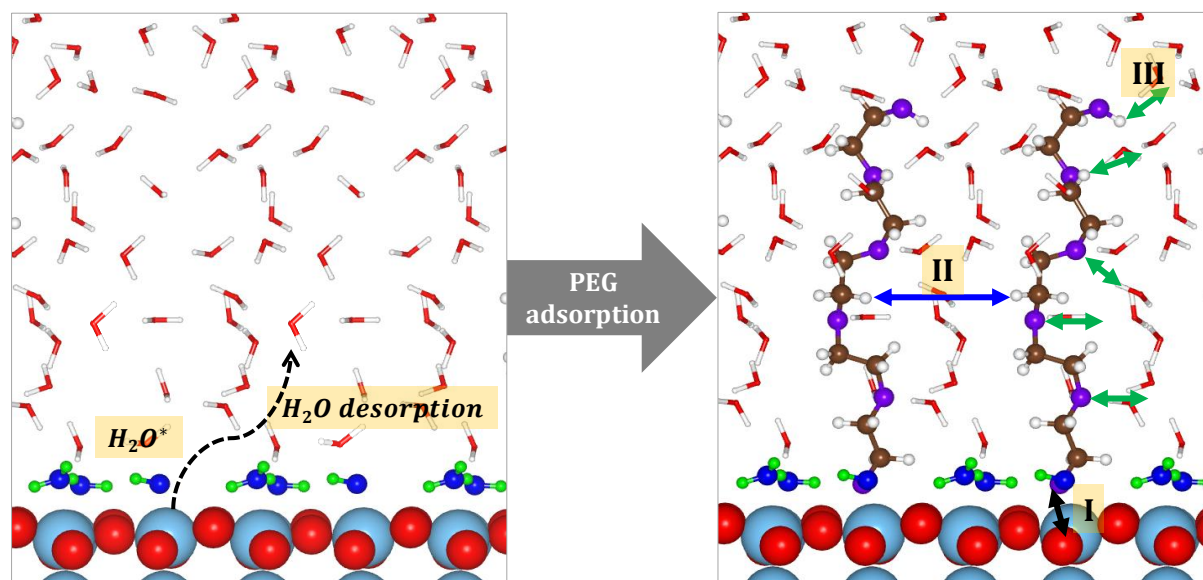


Fig. 1. Schematic side-view illustrations of the PEG adsorption process on hydrated $\text{TiO}_2(001)$. The left panel shows the $\text{H}_2\text{O(l)}/\text{TiO}_2(001)$ interface before PEG adsorption, where surface Ti sites are occupied by molecularly adsorbed water species, denoted as H_2O^* . Upon PEG adsorption, interfacial H_2O molecules are displaced from the TiO_2 surface, leading to the formation of adsorbed PEG species, denoted as PEG^* , as shown in the right panel. The black, blue, and light-green arrows in the right panel indicate PEG^* head-group adsorption on Ti sites (I), inter-chain interactions between neighboring PEG^* chains (II), solvation of PEG^* by surrounding water molecules (III), respectively. Bulk liquid-water molecules are shown in a simplified representation. Color code: light blue, Ti; red, O of TiO_2 ; blue, O of H_2O^* ; light green, H of H_2O^* ; purple, O of PEG^* ; brown, C of PEG^* ; white, H of PEG^* .

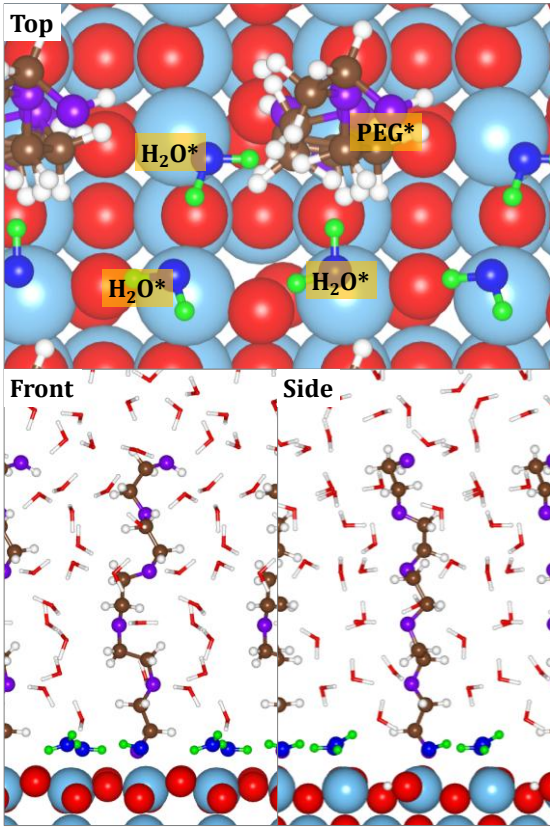
The free energy of PEG adsorption on $\text{TiO}_2(001)$ was decomposed into four main contributions: PEG adsorption enthalpy (ΔH_{PEG^*}), PEG adsorption zero-point energy ($\Delta \text{ZPE}_{\text{PEG}^*}$), PEG adsorption entropy ($T\Delta S_{\text{PEG}^*}$), and H_2O desorption free energy ($\Delta G_{\text{H}_2\text{O}^* \rightarrow \text{H}_2\text{O}(\text{l})}$) [10]. The PEG adsorption enthalpy was further divided into three terms: head-group adsorption to surface Ti sites ($E_{\text{DFT}_{\text{PEG_head}^*}(\text{adsorption})}$), inter-chain interactions between neighboring PEG molecules ($E_{\text{DFT}_{\text{PEG_chain}^*}(\text{interaction})}$), and PEG–water solvation interactions ($E_{\text{DFT}_{\text{PEG}^*}(\text{solvation})}$) (see Fig. 1). The coverage-dependent enthalpic terms were obtained from DFT-AIMD sampled structures.

The entropic contribution associated with PEG adsorption can, in principle, be evaluated using the potential of mean force method [10,32]. In the present work, as a first-order approximation, the PEG adsorption entropy previously obtained for PEG adsorption on $\text{TiO}_2(101)$ was adopted for the $\text{TiO}_2(001)$ analysis. This approximation is based on the assumption that the dominant contribution to the entropy loss arises from the restriction of PEG chain conformations upon adsorption, rather than from facet-specific local bonding interactions [33,34]. Therefore, although the absolute adsorption free energies may involve some uncertainty associated with this approximation, the calculated values are mainly used to discuss the relative coverage-dependent trend in PEG adsorption thermodynamics.

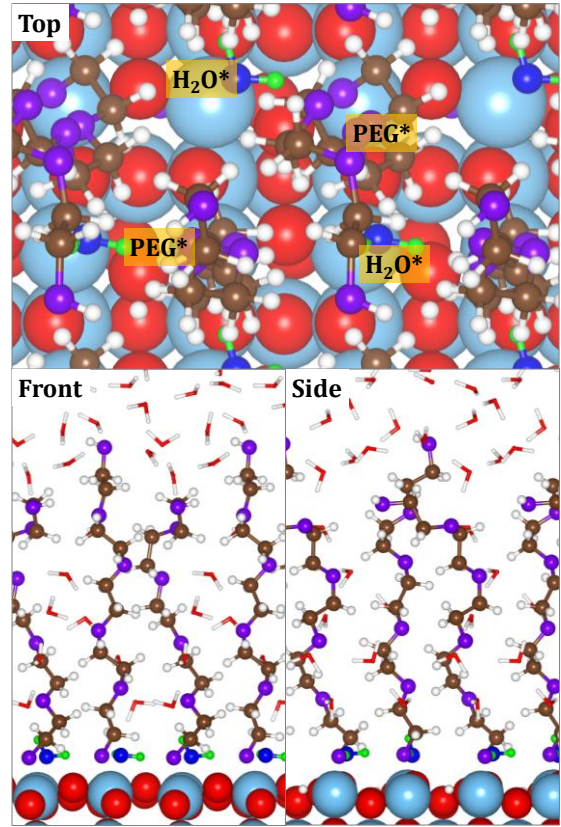
The H_2O desorption free energy was calculated using surface-adsorbed water molecules obtained from the AIMD-sampled structures (see Fig. 1). It is generally known that H_2O tends to adsorb dissociatively on $\text{TiO}_2(001)$ under vacuum conditions, unlike on $\text{TiO}_2(101)$ [35,36]. In the present liquid-water interface model, dissociation of surface-adsorbed H_2O was not observed within the 10 ps AIMD trajectories sampled in this work. Instead, the adsorbed H_2O^* molecules remained molecularly adsorbed and formed hydrogen bonds with surrounding liquid-water molecules. This observation suggests that molecularly adsorbed H_2O can be stabilized at the $\text{TiO}_2(001)$ /liquid-water interface through hydrogen bonding with the surrounding solvent environment. The calculated desorption free energy of a water molecule was 0.08 eV, which is in close agreement with previously reported computational values [37,38], and this value was included in the calculation of the PEG adsorption free energy.

3.1. ΔH_{PEG^*} of PEG-5* on $\text{TiO}_2(001)$

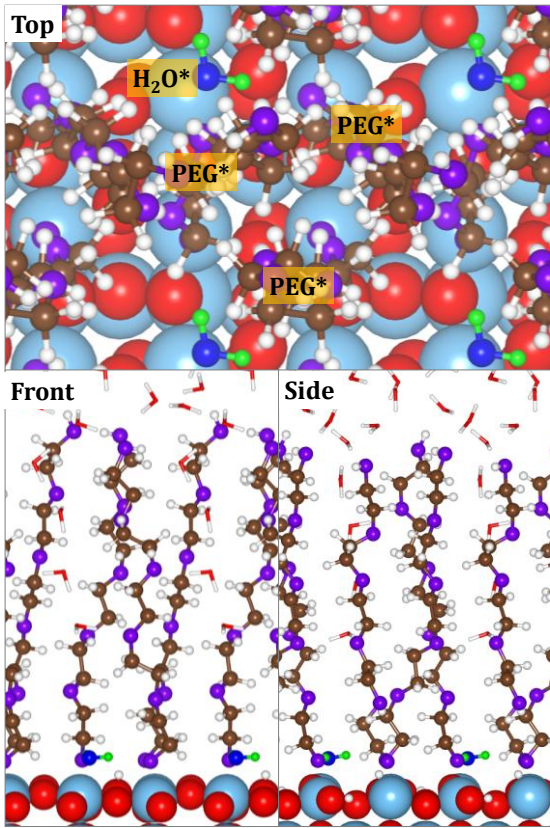
Fig. 2 shows representative AIMD snapshots of PEG-5* on $\text{TiO}_2(001)$ after 10 ps at PEG coverages of 0.25, 0.50, 0.75, and 1.00 monolayer (ML). At 0.25 ML, the adsorbed PEG-5 chain is relatively isolated on the $\text{TiO}_2(001)$ surface, and the remaining exposed Ti sites are largely occupied by molecularly adsorbed water species, denoted as H_2O^* . The front and side views show that PEG-5 chains adopt brush-like configurations, extending from the $\text{TiO}_2(001)$ surface toward the liquid-water region while being solvated by surrounding water molecules.



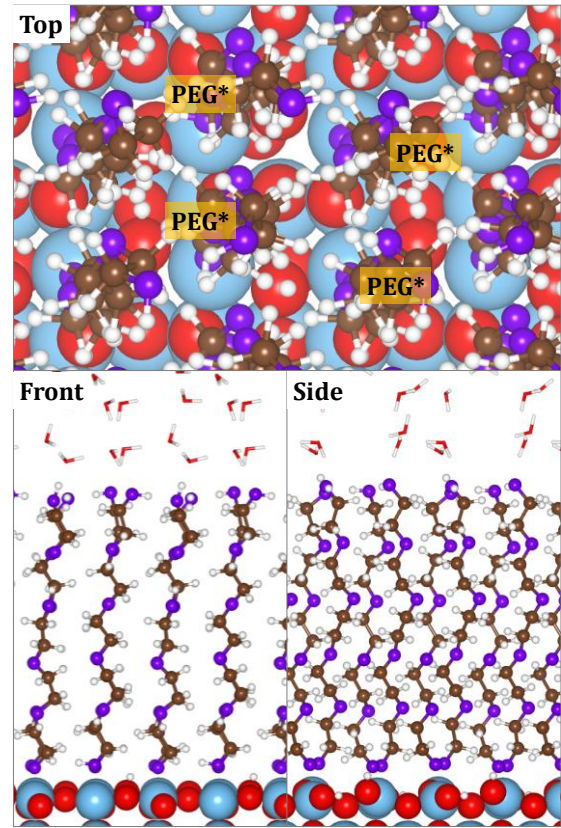
(a)



(b)



(c)



(d)

Fig. 2. Representative AIMD snapshots of PEG-5 adsorbed on hydrated $\text{TiO}_2(001)$ after 10 ps. Top, front, and side views are shown for PEG* coverages of (a) 0.25, (b) 0.50, (c) 0.75, and (d) 1.00 ML. Molecularly adsorbed water species on exposed surface Ti sites are denoted as H_2O^* , while adsorbed PEG-5 species are denoted as PEG*. Bulk liquid-water molecules are shown in a simplified representation in the front and side views, and are omitted from the top views for clarity. Color code: light blue, Ti; red, O of TiO_2 ; blue, O of H_2O^* ; light green, H of H_2O^* ; purple, O of PEG*; brown, C of PEG*; white, H of PEG*.

To quantify the degree of inter-chain overlap, R_F/D_m was used as a dimensionless descriptor, where R_F is the Flory radius of PEG-5 and D_m is the average distance between neighboring PEG chains on the $\text{TiO}_2(001)$ surface. It has been reported that polymers preferentially adopt brush-like conformations when R_F/D_m exceeds approximately 1.00 [39,40]. In the present systems, the R_F/D_m values are 2.00, 2.94, 3.54, and 4.40 at PEG coverages of 0.25, 0.50, 0.75, and 1.00 ML, respectively, indicating that all coverages fall within the brush regime.

As the PEG coverage increases, neighboring PEG chains become progressively closer, leading to enhanced inter-chain overlap and steric crowding. At 0.50 ML, adsorbed water molecules are still observed between PEG chains, whereas at 0.75 and 1.00 ML, PEG molecules occupy a larger fraction of the interfacial region and partially displace H_2O^* from the $\text{TiO}_2(001)$ surface. These structural changes indicate that the coverage-dependent adsorption behavior of PEG on $\text{TiO}_2(001)$ is governed by a balance among PEG–surface binding, PEG inter-chain interactions, PEG–water solvation, and water displacement from the oxide surface.

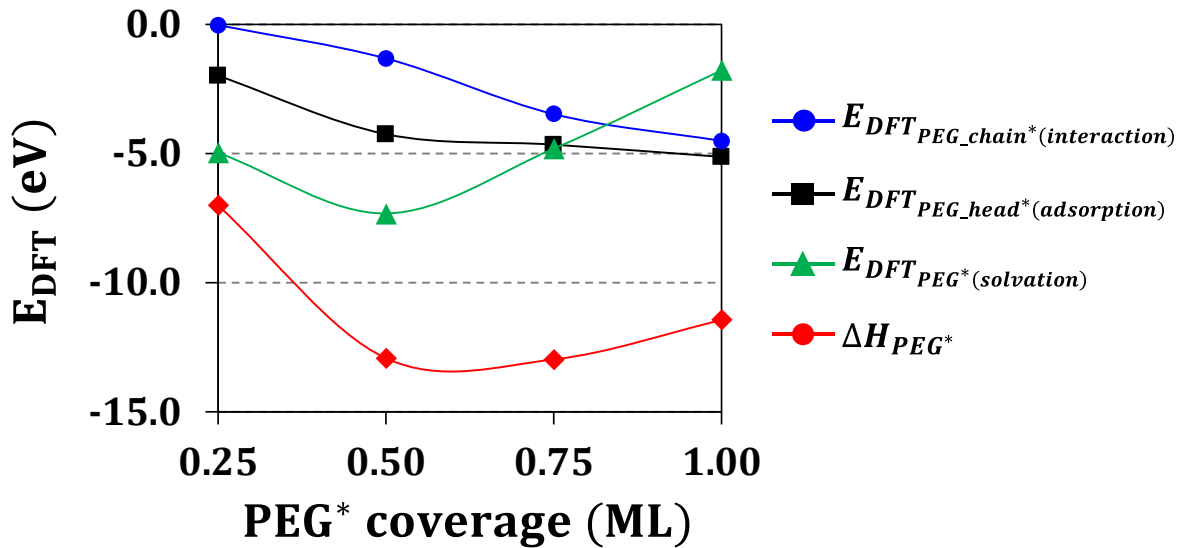


Fig. 3. Coverage-dependent enthalpic contributions to PEG-5 adsorption on hydrated $\text{TiO}_2(001)$ as a function of PEG* coverage. The PEG adsorption enthalpy, ΔH_{PEG^*} , is decomposed into the head-group adsorption energy, $E_{DFT_{PEG_head^*}(adsorption)}$, inter-chain interaction energy, $E_{DFT_{PEG_chain^*}(interaction)}$, and PEG–water solvation energy, $E_{DFT_{PEG^*}(solvation)}$. Negative values indicate enthalpic stabilization of the adsorbed PEG layer.

Fig. 3 presents the coverage-dependent enthalpic contributions to PEG-5 adsorption on $\text{TiO}_2(001)$. The total PEG adsorption enthalpy, ΔH_{PEG^*} , remains negative over the entire coverage range, indicating that PEG adsorption on

the hydrated $\text{TiO}_2(001)$ surface is enthalpically favorable. At 0.25 ML, the stabilization mainly originates from PEG–water solvation, whereas the head-group adsorption contribution is relatively small. As the PEG coverage increases to 0.50 ML, ΔH_{PEG^*} becomes significantly more favorable because both PEG–water solvation and inter-chain interactions are enhanced. This suggests that, in the intermediate coverage regime, neighboring PEG chains can interact with each other while still maintaining sufficient contact with surrounding water molecules.

Further increasing the coverage to 0.75 ML gives a similarly favorable ΔH_{PEG^*} , but the relative balance among the enthalpic terms changes. The head-group adsorption and inter-chain interaction terms become more stabilizing with increasing PEG coverage, reflecting the larger number of PEG–surface contacts and closer packing of PEG chains. In contrast, the PEG–water solvation contribution becomes less favorable at high coverage, especially at 1.00 ML. This weakening of PEG–water solvation is consistent with the dense brush-like interfacial structure observed in Fig. 2, where PEG chains occupy a larger fraction of the interfacial region and reduce the accessibility of water molecules to the PEG chains. As a result, ΔH_{PEG^*} becomes less favorable at 1.00 ML despite the increased stabilization from PEG–surface and inter-chain interactions. These results indicate that the enthalpic driving force for PEG adsorption on $\text{TiO}_2(001)$ is maximized at intermediate coverages, where favorable inter-chain interactions and PEG hydration are optimally balanced. Therefore, the saturated PEG coverage cannot be determined solely by PEG–surface binding, but should be understood as the result of competing enthalpic contributions associated with surface adsorption, chain packing, and solvation at the aqueous oxide interface.

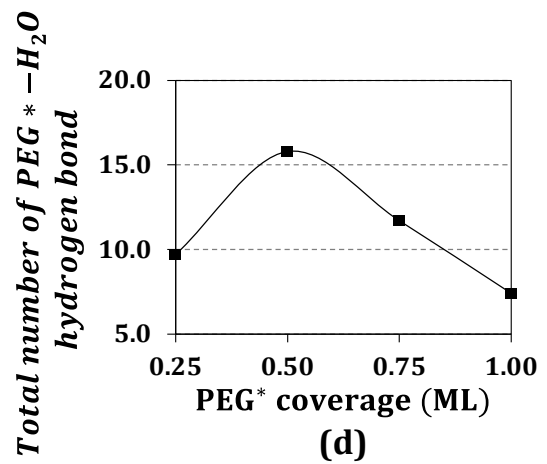
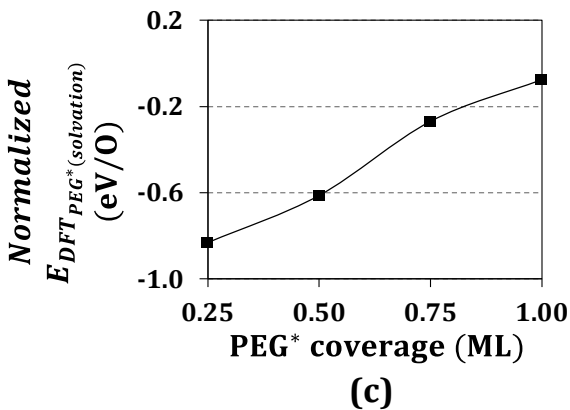
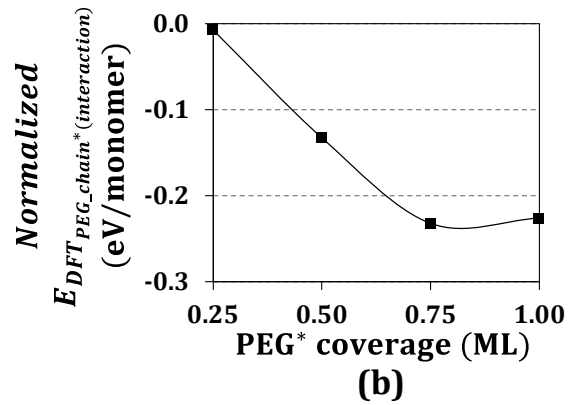
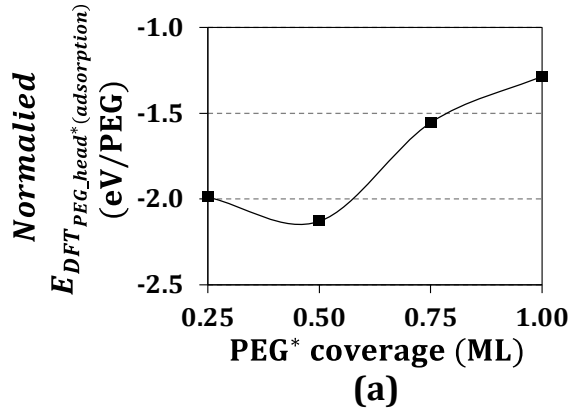


Fig. 4. Coverage-dependent normalized enthalpic contributions and PEG–water hydrogen bonding for PEG-5* adsorption on hydrated $\text{TiO}_2(001)$: (a) normalized $E_{DFT_{PEG_head^*}(adsorption)}$, (b) normalized $E_{DFT_{PEG_chain^*}(interaction)}$, (c) normalized $E_{DFT_{PEG^*}(solvation)}$, and (d) the total number of the hydrogen bonds between PEG-5* and water molecules. The normalized energies are given per adsorbed PEG-5 molecule, per PEG monomer, and per PEG oxygen atom for the head-group adsorption, inter-chain interaction, and PEG–water solvation terms, respectively.

Fig. 4 further analyzes the origin of the coverage-dependent enthalpic behavior by normalizing each contribution with respect to its relevant molecular unit. The normalized head-group adsorption energy (Fig. 4 (a)) is most favorable at 0.25–0.50 ML, but becomes progressively less favorable at higher coverages. This indicates that although the total PEG–surface adsorption contribution increases with PEG coverage, the average stabilization per adsorbed PEG-5 molecule is weakened under densely packed conditions. At high PEG coverage, the local environment around surface Ti sites can be substantially modified by neighboring PEG chains and displaced interfacial water molecules. Such changes may alter the local electronic structure and Lewis acidity of the surface Ti sites, thereby weakening the interaction between the PEG terminal hydroxyl group and $\text{TiO}_2(001)$ [41–43]. In addition, steric crowding among adjacent PEG chains can further reduce the accessibility and optimal binding geometry of individual head groups. Therefore, the less favorable normalized head-group adsorption energy at high coverage suggests that PEG adsorption is not simply additive with increasing coverage, but is affected by coverage-induced changes in both the local Ti surface environment and inter-chain packing.

The normalized inter-chain interaction energy becomes increasingly negative as the PEG coverage increases from 0.25 to 0.75 ML and then remains nearly unchanged at 1.00 ML (Fig. 4 (b)). This behavior shows that attractive PEG–PEG interactions are enhanced as neighboring chains become closer, but the stabilization reaches a nearly saturated level once the PEG layer becomes densely packed. In contrast, the normalized PEG–water solvation energy becomes continuously less favorable with increasing coverage (Fig. 4 (c)). This trend suggests that the hydration of PEG oxygen atoms becomes less effective at high coverage, owing to the reduced accessibility of water molecules within the dense PEG brush layer observed in Fig. 2.

The change in PEG–water hydrogen bonding provides further support for this interpretation (Fig. 4 (d)). The total number of hydrogen bonds between PEG-5* and liquid-water increases from 0.25 to 0.50 ML, indicating enhanced PEG hydration in the intermediate coverage regime. However, it decreases markedly at 0.75 and 1.00 ML despite the larger amount of adsorbed PEG. This result indicates that water molecules are progressively excluded from the PEG-rich interfacial region at high coverage. Therefore, Fig. 4 shows that the weakening of PEG–water solvation at high coverage is directly associated with the loss of PEG–water hydrogen bonding, while the inter-chain interaction becomes saturated. These normalized analyses clarify why the enthalpic stabilization does not continue to increase monotonically with PEG coverage.

3.2. ΔG_{ads} and the saturated coverage of PEG-5* on $\text{TiO}_2(001)$

Table 1 summarizes the adsorption free energy of PEG-5 on $\text{TiO}_2(001)$ by combining the enthalpic, zero-point energy, entropic, and H_2O desorption contributions (details of the individual contributions are provided in Table S5 in the SI.). Although ΔH_{PEG^*} is favorable over the entire coverage range, the final adsorption free energy,

ΔG_{ads} , shows a non-monotonic coverage dependence mainly because the entropic penalty becomes increasingly significant at higher PEG coverages. In contrast, the ZPE correction and H₂O desorption contributions are relatively small compared with the enthalpic and entropic terms. As a result, the thermodynamic stabilization gained from PEG adsorption is mainly offset by the loss of conformational freedom of the PEG chains at high coverages.

The magnitude of ΔG_{ads} strongly depends on PEG coverage. The most favorable adsorption free energy is obtained at 0.50 ML, with $\Delta G_{ads} = -7.85$ eV. When the coverage is increased to 0.75 ML, ΔG_{ads} becomes less favorable despite the similar ΔH_{PEG^*} value, mainly because the entropic penalty increases with the number of adsorbed PEG chains. At 1.00 ML, ΔG_{ads} is further weakened to -1.30 eV, indicating that dense PEG packing significantly reduces the net thermodynamic driving force for adsorption. To further evaluate the thermodynamic preference for additional PEG adsorption, the differential adsorption free energy, ΔG_{diff} , was estimated (see Table 1) [44,45]. The calculated ΔG_{diff} values are -4.47 , -3.38 , 2.48 , and 4.07 eV for increasing the PEG coverage to 0.25, 0.50, 0.75, and 1.00 ML, respectively. The negative ΔG_{diff} values up to 0.50 ML indicate that additional PEG adsorption is thermodynamically favorable in the low-to-intermediate coverage regime. However, ΔG_{diff} becomes positive beyond 0.50 ML, showing that further PEG adsorption is no longer favorable despite the total ΔG_{ads} remaining negative. Therefore, the saturated PEG-5 coverage on hydrated TiO₂(001) is predicted to be 0.50 ML, where the corresponding PEG-5 surface density is 3.49 molecules/nm² (see Table 2).

Table 1. Data for ΔG_{ads} of PEG-5* on TiO₂(001)

Coverage (ML)	ΔH_{PEG^*} (eV) ¹⁾	ΔZPE_{PEG^*} (eV) ¹⁾	$-T\Delta S_{PEG^*}$ (eV) ²⁾	$N^3)$	Total H ₂ O* desorption energy (eV) ⁴⁾	ΔG_{ads} (eV) ⁵⁾	$\Delta G_{diff}(n)$ (eV) ⁶⁾
0.25	-7.01	0.17	2.29	1	0.08	-4.47	-4.47
0.50	-12.93	0.34	4.58	2	0.16	-7.85	-3.38
0.75	-12.98	0.50	6.87	3	0.24	-5.37	2.48
1.00	-11.45	0.67	9.16	4	0.32	-1.30	4.07

¹⁾ the values are from Tables S1-S4 in the SI ($\Delta H_{PEG^*} = E_{DFT_{PEG_head^*}(adsorption)} + E_{DFT_{PEG_chain^*}(interaction)} + E_{DFT_{PEG^*}(solvation)}$)

²⁾ The values were adopted from Ref. [10].

³⁾ the total number of desorbed H₂O*/unit cell during PEG adsorption

⁴⁾ Total H₂O* desorption energy = $n \times$ H₂O* desorption energy

⁵⁾ $\Delta G_{ads} = \Delta H_{PEG^*} + \Delta ZPE_{PEG^*} - T\Delta S_{PEG^*} +$ Total H₂O* desorption energy

⁶⁾ $\Delta G_{diff}(n) = \Delta G_{ads}(n) - \Delta G_{ads}(n-1)$, where n is the number of adsorbed PEG-5 molecules in the unit cell. Here, n = 1, 2, 3, and 4 correspond to PEG-5 coverages of 0.25, 0.50, 0.75, and 1.00 ML, respectively.

Table 2. Surface density of PEG-5* on the TiO₂(001) surfaces

PEG-5* coverage (ML)	Density of PEG-5* (molecules/nm ²)
0.25	1.75
0.50	3.49
0.75	5.24
1.00	6.99

3.3. GPR-based free energy landscape of PEG-5* on TiO₂(001)

Fig. 5 shows the GPR-interpolated adsorption free energy profile as a function of PEG coverage, together with

the individual 1–10 ps AIMD-sampled data points and the mean $\pm$ standard deviation at each coverage (the corresponding numerical data for the GPR interpolation and bootstrap analysis are provided in Tables S6–S9 in the SI). The interpolation captures the non-monotonic coverage dependence obtained from the direct thermodynamic analysis in Table 1. Specifically, the adsorption free energy becomes more favorable as the PEG coverage increases from 0.25 to 0.50 ML, whereas further increases in coverage lead to a weakening of the thermodynamic driving force for adsorption. The minimum of the GPR-interpolated profile appears near the explicitly sampled 0.50 ML point, at approximately 0.51 ML, with an interpolated adsorption free energy of -8.11 eV. This result should therefore be interpreted not as a separate prediction of the saturated coverage, but as a smoothed interpolation consistent with the discrete DFT-AIMD free energy values.

Bootstrap resampling was further performed to evaluate how the finite number of AIMD snapshots affects the interpolated free energy profile. The shaded region in Fig. 5 represents the 95% bootstrap confidence interval obtained from repeated resampling and retraining of the GPR model. Around the minimum region, the confidence interval is relatively narrow, ranging from -8.26 to -7.96 eV. This indicates that the interpolated free energy profile near 0.50 ML is not strongly altered by the particular selection of AIMD snapshots used in the resampling procedure. Thus, the bootstrap analysis provides a statistical measure of the uncertainty associated with the GPR interpolation of the sampled DFT-AIMD data.

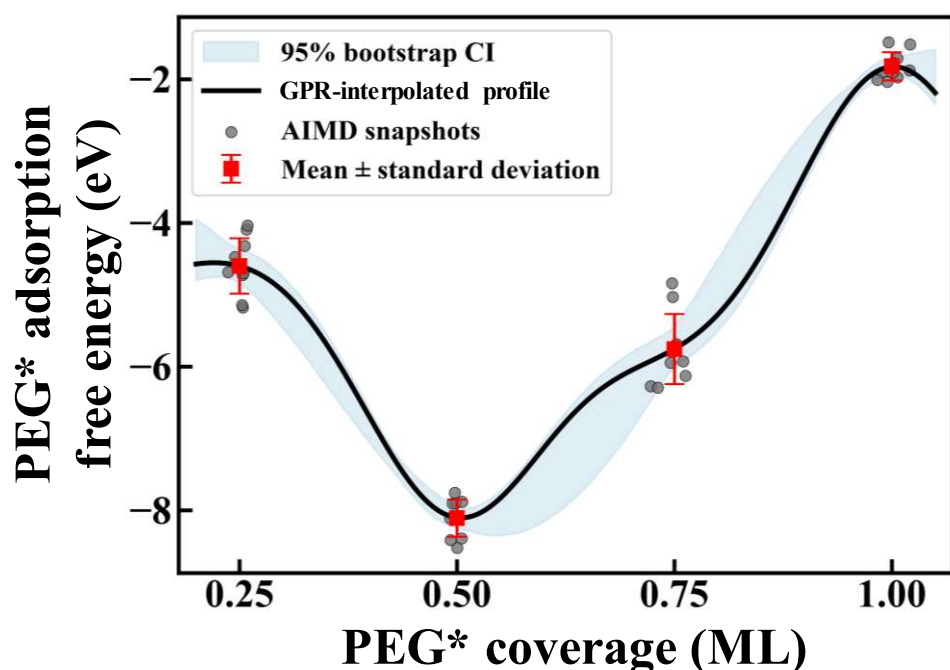


Fig. 5. GPR-interpolated PEG* adsorption free energy profile as a function of PEG coverage at the $\text{TiO}_2(001)$ /liquid-water interface. The gray circles represent individual AIMD-sampled snapshots collected from the 1–10 ps trajectories, while the red squares and error bars indicate the mean $\pm$ standard deviation at each PEG coverage. The black line represents the GPR-interpolated profile, and the light-blue shaded region denotes the 95% bootstrap confidence interval.

4. Conclusions

In this study, the coverage-dependent adsorption thermodynamics of PEG-5 on anatase $\text{TiO}_2(001)$ at the liquid-water interface were investigated using a free energy-based computational framework combining DFT, AIMD simulations, and GPR-based interpolation. PEG adsorption was analyzed at coverages of 0.25, 0.50, 0.75, and 1.00 ML by decomposing the adsorption free energy into PEG adsorption enthalpy, zero-point energy, entropic penalty, and H_2O desorption contributions. The PEG adsorption enthalpy was further separated into head-group adsorption, inter-chain interaction, and PEG–water solvation terms to clarify the molecular origin of the coverage-dependent behavior.

The calculated results show that PEG adsorption on $\text{TiO}_2(001)$ is enthalpically favorable over the entire coverage range. At low-to-intermediate coverages, the adsorption free energy becomes increasingly favorable because PEG chains can maintain strong hydration while also gaining stabilization from inter-chain interactions. The most favorable adsorption free energy was obtained at 0.50 ML, where the competing contributions of PEG head-group binding to the surface, PEG inter-chain interaction, and PEG–water solvation are optimally balanced. In contrast, further increasing the PEG coverage to 0.75 and 1.00 ML weakens the overall thermodynamic driving force for adsorption. This weakening originates from reduced PEG–water solvation, loss of PEG–water hydrogen bonding, less favorable normalized head-group adsorption, and an increasing entropic penalty associated with dense brush-like packing.

The differential adsorption free energy analysis shows that additional PEG adsorption is favorable up to 0.50 ML but becomes thermodynamically unfavorable beyond this coverage. Therefore, the saturated PEG-5 coverage on $\text{TiO}_2(001)$ under liquid-water conditions is predicted to be 0.50 ML, corresponding to a surface density of $3.49 \text{ molecules nm}^{-2}$. GPR interpolation of the AIMD-derived free energy data gives a consistent minimum near 0.51 ML, supporting the thermodynamic preference for intermediate PEG coverage. Overall, this work demonstrates that PEG saturation at the $\text{TiO}_2(001)$ /liquid-water interface cannot be understood solely from PEG–surface binding strength, but is determined by the balance among surface adsorption, inter-chain packing, hydration, water displacement, and conformational entropy. These findings provide a molecular-level thermodynamic basis for controlling PEG coverage on TiO_2 surfaces in aqueous environments.

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