
*ADSORPTION AND PHOTOOXIDATION OF SARS-CoV
2 SPIKE AMINO ACIDS ON TiO₂ POLYMORPHS*

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Abstract

This cumulative doctoral thesis investigates the molecular interactions between biologically relevant amino acids, L-cysteine and L-asparagine, and well-defined titanium dioxide (TiO_2) surfaces, with emphasis on adsorption mechanisms and photocatalytically driven oxidation processes. This work was initiated within the CORAERO project (Grant KA1-Co-06), which investigated airborne transmission routes of the SARS-CoV-2 and explored photocatalytic strategies for viral inactivation. TiO_2 was selected as a model photocatalyst due to its established antimicrobial activity against a broad range of pathogens. Despite this proven performance, the molecular mechanisms governing interactions between biomolecules and TiO_2 surfaces remain unclear. This work examines how representative biomolecular building blocks, namely amino acids, adsorb and interact on TiO_2 surfaces and how these processes contribute to chemical pathways leading to the inactivation of larger biological systems such as viruses.

A surface science approach allows adsorption geometries, surface coordination, and light-driven transformations to be resolved with atomic scale detail. Single crystalline rutile $\text{TiO}_2(110)$ and anatase $\text{TiO}_2(101)$ surfaces serve as model systems, enabling a controlled comparison between two technologically relevant TiO_2 polymorphs. The amino acids L-cysteine and L-asparagine were selected as representative protein building blocks with chemically distinct functional groups in their side chain. The experimental methodology combines ultrahigh vacuum (UHV) sample preparation, scanning tunnelling microscopy (STM), X-ray photoelectron spectroscopy (XPS), and Fourier-transform infrared reflection-absorption spectroscopy (FT-IRRAS) methods, supported by density functional theory (DFT) calculations.

Cysteine adsorption on rutile $\text{TiO}_2(110)$ is considerably more complex than previously assumed. Three adsorption configurations coexist at room temperature: a deprotonated or zwitterionic bridging bidentate $\text{DP}(\text{O},\text{O})/\text{ZW}(\text{O},\text{O})$ carboxylate geometry, a deprotonated $\text{DP}(\text{O},\text{N})$ configuration involving the amino group, and a mixed $\text{DP}(\text{O},\text{S})$ configuration in which sulphur directly coordinates to surface Ti sites without C-S bond cleavage. STM reveals adsorption confined to Ti_{5c} rows and dimer formation even at low coverage. XPS identifies both thiol (S-H) and thiolate (S-Ti) species confirming bond formation between the thiol group and the surface and together with FT-IRRAS demonstrate multiple protonation states for the amino group.

Cysteine adsorption on anatase $\text{TiO}_2(101)$ shows a different behaviour compared with rutile $\text{TiO}_2(110)$. STM reveals adsorption both on terraces and at step edges. XPS and FT-IRRAS indicate a high abundance of neutral NH_2 species together with sulphur present in both S-H and S-Ti species, consistent with adsorption geometries involving direct coordination of nitrogen and sulphur to surface Ti atoms. Density functional theory calculations identify two nearly degenerate adsorption configurations, molecular $\text{M}(\text{N},\text{S})$ and $\text{DP}(\text{O},\text{N})$, with additional contributions from $\text{DP}(\text{O},\text{S})$, whereas bridging carboxylate configurations such as $\text{DP}(\text{O},\text{O})/\text{ZW}(\text{O},\text{O})$ are largely suppressed. Under UV illumination in air, cysteine undergoes selective photooxidation at the thiol group of the side chain, progressing from thiol species through intermediate oxidation states to fully oxidized sulfonic acid. This work provides the first experimental evidence of cysteine adsorption and photooxidation on anatase TiO_2 single crystals.

The adsorption of L-asparagine on rutile $\text{TiO}_2(110)$ and anatase $\text{TiO}_2(101)$ further highlights the influence of surface structure on amino acid binding. On both polymorphs, XPS and FT-IRRAS show adsorption through a deprotonated carboxylate group while the amide side chain remains

intact. However, the relative stability of adsorption geometries differs between the two surfaces. Rutile $\text{TiO}_2(110)$ predominantly stabilizes a bridging bidentate (O,O) configuration, as observed by STM as adsorbates aligned along Ti_{5c} rows. In contrast, anatase $\text{TiO}_2(101)$ stabilizes a larger proportion of (O,N) geometries, consistent with the larger Ti_{5c} – Ti_{5c} separation of the anatase surface, which favors adsorption involving simultaneous coordination of oxygen and nitrogen atoms. As a consequence, XPS shows a higher proportion of protonated NH_3^+ species on rutile, whereas on anatase the amino group more frequently binds directly to surface Ti atoms and therefore remains in the neutral NH_2 form.

Together, these results establish molecular-level adsorption models for cysteine and asparagine on rutile $\text{TiO}_2(110)$ and anatase $\text{TiO}_2(101)$ and reveal a selective stepwise sulphur photooxidation pathway for cysteine on anatase leading to sulfonic acid formation. They demonstrate that differences in Ti_{5c} – Ti_{5c} spacing between rutile and anatase determine the stability of (O,O) and mixed (O,N)/(N,S) adsorption geometries and thereby control biomolecule binding and photocatalytic reactivity on TiO_2 surfaces.

Zusammenfassung

Diese kumulative Dissertation untersucht die molekularen Wechselwirkungen zwischen biologisch relevanten Aminosäuren und wohldefinierten Titandioxid-(TiO₂)-Oberflächen, mit besonderem Schwerpunkt auf Adsorptionsmechanismen und photokatalytisch getriebenen Oxidationsprozessen. Diese Arbeit wurde im Rahmen des CORAERO-Projekts (Förderkennzeichen KA1-Co-06) initiiert, das luftgetragene Übertragungswege von Coronaviren sowie photokatalytische Strategien zu deren Inaktivierung untersuchte. TiO₂ wurde aufgrund seiner etablierten antimikrobiellen Aktivität gegenüber einem breiten Spektrum von Pathogenen als Modell-Photokatalysator ausgewählt. Trotz dieser nachgewiesenen Leistungsfähigkeit sind die molekularen Mechanismen, die die Wechselwirkungen zwischen Biomolekülen und TiO₂-Oberflächen bestimmen, weiterhin nur unzureichend verstanden. Diese Arbeit untersucht, wie repräsentative biomolekulare Bausteine, insbesondere Aminosäuren, an TiO₂-Oberflächen adsorbieren und dort reagieren. Darüber hinaus wird analysiert, wie diese Prozesse zu chemischen Reaktionswegen beitragen, die zur Inaktivierung größerer Biomoleküle führen.

Ein oberflächenwissenschaftlicher Ansatz ermöglicht es, Adsorptionsgeometrien, Oberflächenkoordination und lichtinduzierte Transformationen mit atomarer Auflösung zu untersuchen. Einkristalline Rutil-TiO₂(110)- und Anatas-TiO₂(101)-Oberflächen dienen dabei als Modellsysteme und erlauben einen kontrollierten Vergleich zweier technologisch relevanter TiO₂-Polymorphe. Die Aminosäuren L-Cystein und L-Asparagin wurden als repräsentative Proteinbausteine mit chemisch unterschiedlichen Seitenketten ausgewählt. Die experimentelle Methodik kombiniert Ultrahochvakuum-Probenpräparation mit Rastertunnelmikroskopie (STM), Röntgenphotoelektronenspektroskopie (XPS) und Fourier-Transform-Infrarot-Reflexions-

Absorptionsspektroskopie (FT-IRRAS), unterstützt durch Dichtefunktionaltheorie-(DFT)-Berechnungen.

Die Adsorption von Cystein auf Rutil-TiO₂(110) ist deutlich komplexer als bislang angenommen. Bei Raumtemperatur koexistieren drei Adsorptionskonfigurationen: eine deprotonierte oder zwitterionische, brückenbildende bidentate DP(O,O)/ZW(O,O)-Carboxylat-Geometrie, eine deprotonierte DP(O,N)-Konfiguration unter Beteiligung der Aminogruppe sowie eine gemischte DP(O,S)-Konfiguration, bei der Schwefel ohne Spaltung der C-S-Bindung direkt an Oberflächen-Ti-Zentren koordiniert. STM zeigt eine auf Ti_{5c}-Reihen beschränkte Adsorption sowie die Bildung von Dimeren bereits bei niedriger Bedeckung. XPS identifiziert sowohl Thiol- (S-H) als auch Thiolat-Spezies (S-Ti) und bestätigt damit die Bindung der Thiolgruppe an die Oberfläche, während FT-IRRAS zusammen mit XPS das Vorliegen mehrerer Protonierungszustände der Aminogruppe nachweist.

Die Adsorption von Cystein auf Anatas-TiO₂(101) zeigt ein deutlich anderes Verhalten als auf Rutil-TiO₂(110). STM zeigt Adsorption sowohl auf Terrassen als auch an Stufenkanten. XPS und FT-IRRAS weisen einen hohen Anteil neutraler NH₂-Spezies sowie Schwefel sowohl in S-H- als auch in S-Ti-Spezies nach, was auf Adsorptionsgeometrien mit direkter Koordination von Stickstoff und Schwefel an Oberflächen-Ti-Atome hinweist. DFT-Berechnungen identifizieren zwei nahezu energetisch entartete Adsorptionskonfigurationen, eine molekulare M(N,S)-Geometrie und eine DP(O,N)-Geometrie, mit zusätzlichen Beiträgen von DP(O,S), während brückenbildende Carboxylatkonfigurationen wie DP(O,O)/ZW(O,O) auf Anatas weitgehend unterdrückt sind. Unter UV-Beleuchtung an Luft durchläuft Cystein eine selektive Photooxidation an der Thiolgruppe der Seitenkette, die von Thiol-Spezies über intermediäre Oxidationszustände

bis zu vollständig oxidierte Sulfonsäure fortschreitet. Diese Arbeit liefert den ersten experimentellen Nachweis der Adsorption und Photooxidation von Cystein auf einkristallinen Anatas-TiO₂-Oberflächen.

Die Adsorption von L-Asparagin auf Rutil-TiO₂(110) und Anatas-TiO₂(101) verdeutlicht zusätzlich den Einfluss der Oberflächenstruktur auf die Bindung von Aminosäuren. Auf beiden Polymorphen zeigen XPS und FT-IRRAS eine Adsorption über eine deprotonierte Carboxylatgruppe, während die Amid-Seitenkette intakt bleibt. Die relative Stabilität der Adsorptionsgeometrien unterscheidet sich jedoch deutlich zwischen den beiden Oberflächen. Rutil-TiO₂(110) stabilisiert überwiegend eine brückenbildende bidentate (O,O)-Konfiguration, die im STM als entlang der Ti_{5c}-Reihen ausgerichtete Adsorbate beobachtet wird. Im Gegensatz dazu stabilisiert Anatas-TiO₂(101) einen größeren Anteil gemischter (O,N)-Geometrien, was mit dem größeren Ti_{5c}-Ti_{5c}-Abstand der Anatas-Oberfläche konsistent ist, der Adsorptionskonfigurationen mit gleichzeitiger Koordination von Sauerstoff und Stickstoff begünstigt. Entsprechend zeigt XPS auf Rutil einen höheren Anteil protonierter NH₃⁺-Spezies, während auf Anatas die Aminogruppe häufiger direkt an Oberflächen-Ti-Atome bindet und daher überwiegend in der neutralen NH₂-Form vorliegt.

Zusammenfassend etablieren diese Ergebnisse molekulare Adsorptionsmodelle für Cystein und Asparagin auf Rutil-TiO₂(110) und Anatas-TiO₂(101) und zeigen einen selektiven, schrittweisen Schwefel-Photooxidationsmechanismus für Cystein auf Anatas, der zur Bildung von Sulfonsäure führt. Sie zeigen, dass Unterschiede im Ti_{5c}-Ti_{5c}-Abstand zwischen Rutil und Anatas die Stabilität von (O,O)- und gemischten (O,N)/(N,S)-Adsorptionsgeometrien bestimmen und damit die

Bindung von Biomolekülen sowie deren photokatalytische Reaktivität auf TiO_2 -Oberflächen steuern.

List of Publications

Paper I: Unravelling the Role of the Multi-Functional Groups in the Adsorption of L-Cysteine on Rutile TiO₂(110)

Miguel Blanco Garcia, Daniele Perilli, Chiara Daldossi, Aldo Ugolotti, Martina Giordano, Daniel Silvan Dolling, Michael Wagstaffe, Mona Kohantorabi, Andreas Stierle, Cristiana Di Valentin, Heshmat Noei.

J. Am. Chem. Soc. 2025, 147, 44, 40158–40170 <https://doi.org/10.1021/jacs.5c07119>

I performed all sample preparation, design and realize all experiments in XPS, FT-IRRAS, STM, analysis of all experimental data and manuscript writing.

Paper II: Adsorption and Sulphur-Selective Photooxidation of Cysteine on Anatase TiO₂(101)

Miguel Blanco Garcia, Daniele Perilli, Chiara Daldossi, Aldo Ugolotti, Daniel Silvan Dolling, Andreas Stierle, Annabella Selloni Cristiana Di Valentin, Heshmat Noei.

Manuscript submitted to the Journal of American Chemical Society 2026

I performed all sample preparation, design and realize all experiments in XPS, FT-IRRAS, STM, analysis of all experimental data and manuscript writing.

Paper III: Protonation and Binding Configurations of L-Asparagine on Rutile (110) and Anatase (101) TiO₂ Surfaces

Miguel Blanco Garcia, Andreas Stierle, Heshmat Noei

Manuscript in preparation, 2026

I performed all sample preparation, design and realize all experiments in XPS, FT-IRRAS, STM, analysis of all experimental data and manuscript writing.

Furthermore, I have contributed also to these publications during the doctoral studies.

Paper IV: Light-Induced Transformation of Virus-Like Particles on TiO₂

Mona Kohantorabi, Aldo Ugolotti, Benedikt Sochor, Johannes Roessler, Michael Wagstaffe, Alexander Meinhardt, E. Erik Beck, Daniel Silvan Dolling, Miguel Blanco Garcia, Marcus

Creutzburg, Thomas F. Keller, Matthias Schwartzkopf, Sarathlal Koyiloth Vayalil, Roland Thuenauer, Gabriela Guédez, Christian Löw, Gregor Ebert, Ulrike Protzer, Wolfgang Hammerschmidt, Reinhard Zeidler, Stephan V. Roth, Cristiana Di Valentin, Andreas Stierle And Heshmat Noei

ACS Appl. Mater. Interfaces 2024, 16, 28, 37275–37287 <https://doi.org/10.1021/acsami.4c07151>

I participated in the acquisition of GISAXS data at PETRA III P03 beamlines.

Paper V: In-Situ Growth and Oxidation of Cu Nanoparticles on Rutile TiO₂(110)

Daniel Silvan Dolling, Miguel Blanco, Mona Kohantorabi, Yufeng Zhai, Benedikt Sochor, Mohammad Ebrahim Haji Naghi Tehrani, Jan-Christian Schober, Ming-Chao Kao, Jagrati Dwivedi, Arno Jeromin, Olof Gutowski, Dmitri Novikov, Thomas F. Keller, Stephan V. Roth, Andreas Stierle, and Heshmat Noei

Submitted to The Journal of Physical Chemistry C, 2026

I participated in the sample preparation and acquisition of data at PETRA III P23, P07 (HEXRD) and P03 (GISAXS) beamlines.

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1: Introduction

The outbreak of the COVID-19 pandemic in 2020 highlighted the urgent need for disinfection strategies beyond conventional chemical or thermal treatments. In response, the CORAERO project funded by Helmholtz (Grant KA1-Co-06), to which this thesis belongs, was established to investigate photocatalytic solutions for airborne transmission and surface disinfection. Titanium dioxide (TiO_2), a well-known photocatalyst, was chosen as a model material to generate oxidizing and reducing radicals under ultraviolet or solar light and thereby inactivate viral particles. Previous studies in our group showed that illuminated TiO_2 surfaces can deactivate coronavirus particles (Figure 1.1), but the microscopic mechanisms underlying this antiviral activity remained unclear (RNA damage, protein denaturation, role of generated radicals) (1, 2).

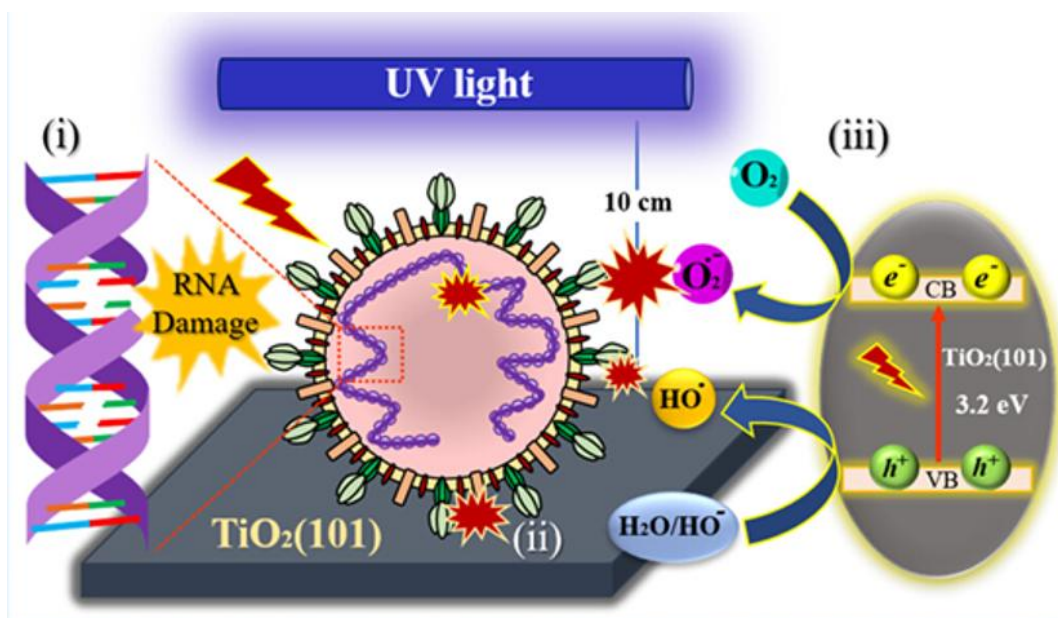


Figure 1.1. Schematic representation of the proposed interaction of SARS-CoV-2 with an anatase $\text{TiO}_2(101)$ surface and the main light driven inactivation routes. The diagram summarizes three conceptually distinct contributions: (i) damage to the viral RNA, (ii) structural alteration of spike proteins and (iii) photocatalytic oxidation at the TiO_2 surface mediated by photogenerated radicals and reactive oxygen species. Figure taken from reference (1).

Viruses are complex structures consisting of nucleic acids enclosed by a protein shell and, in many cases, a lipid envelope. Their inactivation on photocatalytic surfaces involves chemical damage to one or more of these molecular components. Because intact viruses are large and structurally heterogeneous, studying their degradation mechanisms in detail is extremely difficult. Therefore, we adopted a reductionistic strategy: rather than using whole viral particles, we focus on simpler molecular building blocks such as amino acids. As the fundamental units of proteins, amino acids can be used to probe how basic biomolecular components interact with TiO_2 under photocatalytic conditions. These elementary steps constrain plausible pathways for protein damage on TiO_2 under illumination. Since amino acids are present in every biological system, their interaction with photocatalysts is also relevant to antimicrobial coatings and environmental chemistry. Cysteine and asparagine were selected as model systems because both amino acids are abundant in exposed regions of viral surface proteins. Cysteine is of particular interest because it is the only amino acid containing a thiol group, enabling strong site specific binding to metal oxide surfaces and the formation of disulfide bonds that are critical for protein stability and folding. Asparagine, in contrast, provides carboxylate, amine, and amide functionalities without intrinsic redox active side chains.

The use of TiO_2 as a photocatalyst was established by Fujishima and Honda, who in 1972 demonstrated photoelectrochemical water splitting on a TiO_2 electrode under ultraviolet illumination (3). In their experiment, photons with energy above the band gap promoted electrons to the conduction band and left holes in the valence band, which in turn drove hydrogen evolution at a platinum cathode and oxygen evolution at the TiO_2 surface.

In this thesis I focus on the two most common TiO₂ polymorphs, rutile and anatase, which are widely used as model photocatalysts. Both polymorphs absorb ultraviolet light and can generate electron hole pairs that drive redox reactions at the surface, but differ in their crystal structure and electronic properties. These differences, and their consequences in the adsorption and interaction with biomolecules and photoreaction, are discussed in more detail in Chapter 2 (4, 5).

Because of these properties, TiO₂ has been widely explored for environmental remediation. Under irradiation it can degrade a broad range of persistent organic contaminants, including dyes, pesticides, pharmaceuticals and endocrine disruptors (6, 7). Applications include wastewater purification, photocatalytic membranes and catalytic reactors for air cleaning, as well as commercial products such as self-cleaning glass, antimicrobial tiles and photocatalytic building materials (8-10).

Photocatalytic TiO₂ surfaces have been reported to inactivate a range of microorganisms under illumination. Under UV or solar exposure, TiO₂ can damage lipids, proteins and nucleic acids, leading to the inactivation of bacteria, fungi and viruses (11, 12). This antimicrobial effect has been exploited in coatings for medical devices, surgical instruments and hospital surfaces to enable light-driven sterilization without additional chemical disinfectants (13, 14).

The ability of oxide minerals to bind amino acids and nucleic acids is also relevant to prebiotic chemistry. Minerals such as TiO₂ and clays can adsorb and concentrate biomolecular precursors and have been shown to promote peptide-bond formation and nucleotide polymerization into short RNA-like chains (15, 16). These observations support the idea that surface-mediated chemistry on oxides may have contributed to the origin of life. Despite this wide range of contexts, the molecular scale mechanisms that govern TiO₂ interactions with biological matter remain only partially

understood. Chemical modification of proteins at oxide surfaces plays a central role in processes such as photocatalytic disinfection, yet it is difficult to probe these transformations directly in large biological assemblies due to the large number of molecules, interactions between them or effect of solvents. Using amino acids as model systems provides a practical reductionist approach to this problem. Amino acids are present in nearly all biological systems and carry functional groups (-NH₂, -COOH, -OH, -SH) that can bind, transform or react on TiO₂ surfaces (17, 18). Questions such as which functional group preferentially binds, whether intermolecular interactions occur, and whether different groups can bind simultaneously remain unresolved for most amino acids even though surface science studies on single crystalline materials have already shown that cysteine can display complex bonding and stability behaviour depending on the substrate (19). By addressing these questions for cysteine and asparagine and treating them as molecular probes, this thesis aims to understand the bigger picture of how TiO₂ interacts with biological matter under photocatalytic conditions.

The central questions addressed in this work are: (i) which adsorption geometries are stabilized for cysteine and asparagine on rutile TiO₂(110) and anatase TiO₂(101) surfaces, (ii) how surface site geometry changes the adsorption modes, and (iii) what is the photooxidation mechanism of the amino acid transformation under UV illumination.

The thesis is structured as follows. Chapter 2 reviews the state of the art on TiO₂ photocatalysis and on the adsorption and reactivity of amino acids and related molecules. Chapter 3 summarizes the experimental methods used throughout this work, with emphasis on ultrahigh vacuum surface preparation, X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared reflection-absorption spectroscopy (FT-IRRAS) and scanning tunnelling microscopy (STM). Together, these

techniques provide atomic level information on the structure, composition and electronic properties of TiO_2 surfaces and their interaction with adsorbates. Chapter 4 describes the adsorption of cysteine on rutile $\text{TiO}_2(110)$ and is based on an article that has been published in the *Journal of the American Chemical Society* in 2025 (20). Chapter 5 extends this study to the anatase $\text{TiO}_2(101)$ surface, first analyzing the adsorption of cysteine and then its photooxidation under ultraviolet illumination. Chapter 6 presents a comparative study of asparagine adsorption on anatase (101) and rutile (110), highlighting how the TiO_2 polymorph controls binding modes and stability. Finally, Chapter 7 summarizes the main conclusions and outlines possible directions for future investigations.

2: State of the Art

2.1 Titanium Dioxide: Morphology and Electronic Properties

Titanium dioxide crystallizes in several polymorphs, but the two most stable phases at room temperature and the ones relevant to photocatalysis are rutile and anatase. Rutile is the thermodynamically most stable phase under ambient conditions, whereas anatase is metastable and typically forms under low temperature synthesis routes, transforming irreversibly into rutile upon heating to around 900 K, depending on crystallite size and preparation history (21, 22). In both polymorphs, TiO_6 octahedra constitute the fundamental structural units; however, their mode of connection differs. In rutile TiO_2 , the octahedra share edges along the [001] direction and corners in the perpendicular directions, resulting in a more compact structure with relatively small Ti-O-Ti bond angles ($81\text{--}99^\circ$) and a higher density. In contrast, anatase TiO_2 is built from more distorted TiO_6 octahedra, giving rise to larger Ti-O-Ti bond angles ($140\text{--}156^\circ$) and a lower packing density. These differences in octahedral distortion and connectivity are directly reflected in the lattice parameters, unit cell symmetries, and electronic structures of the two phases, as summarized in Table 2.1.1 and illustrated in Figure 2.1.1 (23).

Table 2.1.1. Comparison between structural parameters of rutile and anatase TiO_2 . Data taken from (21).

Property	Rutile	Anatase
Crystal structure	Tetragonal	Tetragonal
Atoms per unit cell (Z)	2	4
Space Group	$P4_2/mnm$	$I4_1/amd$
Lattice Parameter (nm)	$a = b = 0.4594$ $c = 0.2958$	$a = b = 0.3785$ $c = 0.9514$
Unit cell Volume (nm^3)	0.0624	0.1363
Density $\text{kg}\cdot\text{m}^{-3}$	4250	3894
Experimental Band Gap (eV)	~ 3.0 (direct)	~ 3.2 (indirect)
Refractive index	2.79, 2.903	2.54, 2.49

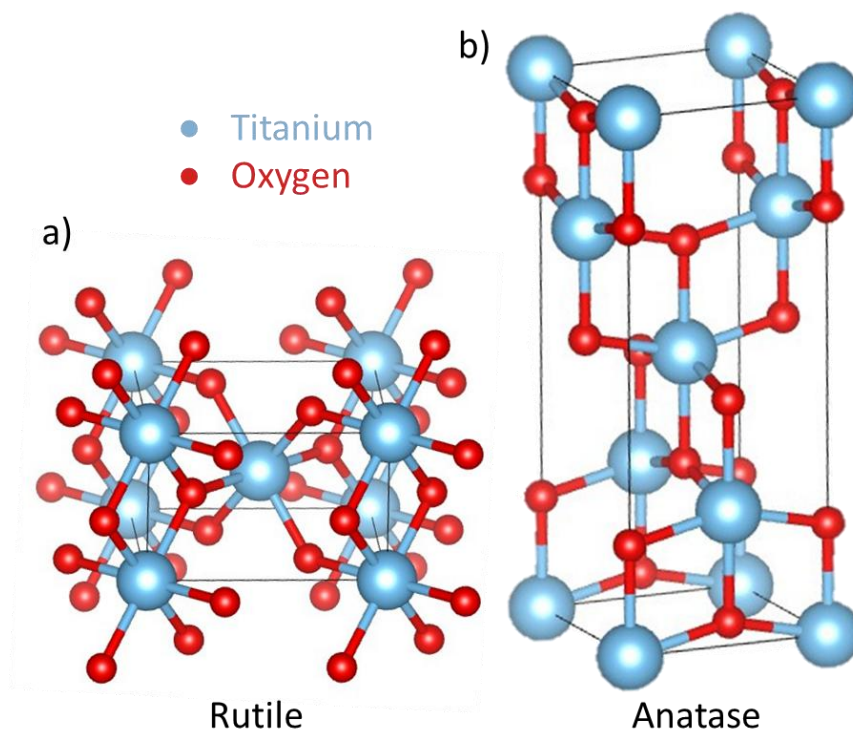


Figure 2.1.1. Unit cell of a) Rutile and b) Anatase. Models drawn using VESTA and unit cell parameters taken from Crystallography Open Database.

In crystalline solids, electrons no longer occupy discrete atomic orbitals but rather extended states that arise from the periodic overlap of those orbitals in the lattice. This interaction causes the original atomic energy levels to split into densely spaced bands of allowed energies separated by forbidden gaps. The translational symmetry of the crystal means that the resulting electronic states can be expressed as Bloch functions, characterized by a wave vector k that acts as the crystal momentum. Because of this structure, optical excitation involves transitions between the valence band and the conduction band, and the nature of these transitions depends critically on how energy and momentum are conserved.

Optical absorption occurs when an incident photon has sufficient energy to promote an electron across the band gap. Because photons, even those with energies in the UV range typical of semiconductor band gaps, carry far less momentum than electrons in a crystal lattice, electronic excitations take place with essentially no change in k . These vertical transitions ($\Delta k \approx 0$) strongly restrict which processes are allowed. When the valence band maximum (VBM) and conduction band minimum (CBM) occur at the same k point, the excitation is direct and does not require any additional interaction. If the VBM and CBM lie at different points in reciprocal space, the transition is indirect and must be assisted by a phonon to conserve momentum. Other pathways, such as plasmon assisted or multiphoton processes, can also fulfil momentum conservation under intense illumination, but they are far less efficient. Consequently, indirect transitions typically occur with much lower probability (24, 25). This is illustrated in Figure 2.1.2, taken from reference (26).

For TiO_2 , the valence band is mainly composed of O 2p states, while the conduction band derives from Ti 3d orbitals. Rutile is commonly reported to have an optical gap of ~ 3.0 eV with predominantly direct character, whereas anatase exhibits an indirect gap of ~ 3.2 eV. From these values alone, one would expect rutile to absorb UV light more efficiently, since direct transitions do not require phonon assistance. However, optical absorption alone does not determine photocatalytic activity. Electron-hole separation and transport strongly influence the efficiency of the photocatalysis (27, 28).

In anatase, the conduction band is more dispersive, giving electrons a lower effective mass and reducing their tendency to localize. After excitation, electrons often migrate into subsurface Ti^{3+} states, while holes remain near the surface, typically stabilized by oxygen or hydroxyl groups. This

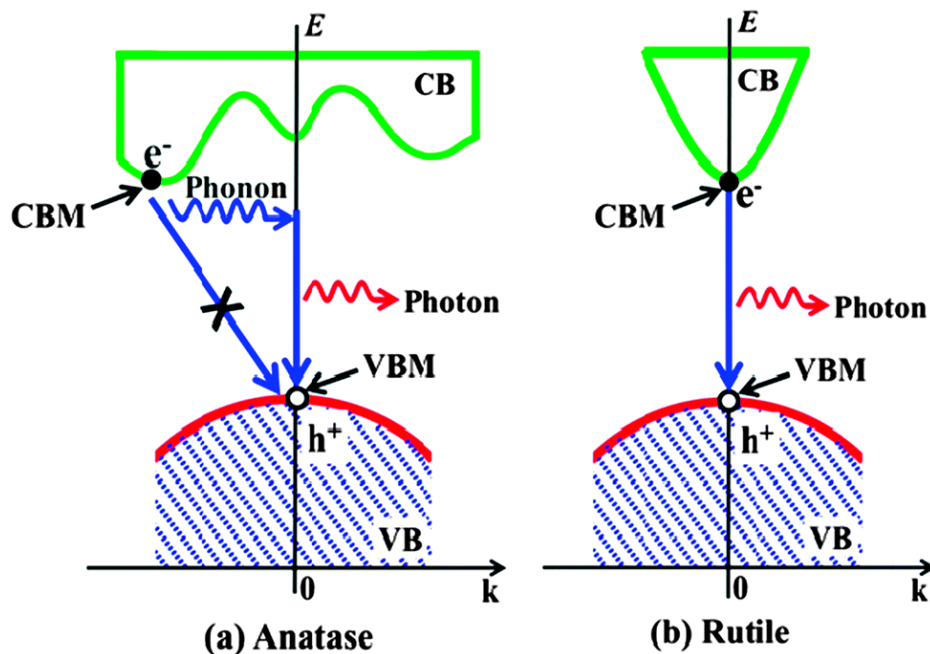


Figure 2.1.2. Schematic $E(k)$ band diagrams showing (a) indirect gap anatase and direct gap rutile (b). Taken from (26).

intrinsic spatial separation suppresses ultrafast recombination and increases carrier lifetimes, which strongly enhances photocatalytic efficiency. In rutile, electrons couple strongly to local lattice distortions and readily self-trap as small polarons, meaning that although rutile absorbs UV photons effectively, most carriers recombine before reaching reactive surface sites. This difference in charge carrier dynamics is widely recognized as the main reason why anatase generally exhibits superior photocatalytic performance (6, 29, 30).

2.2 Rutile (110) and Anatase (101) Surfaces of TiO_2

The rutile $\text{TiO}_2(110)$ surface is the most studied model surface of this polymorph and has been characterized in great detail over the past decades. Its stoichiometric (1×1) termination consists of parallel rows of fivefold coordinated titanium atoms (Ti_{5c}) separated by rows of bridging oxygen atoms that run along the $[001]$ direction. In scanning tunnelling microscopy (STM), the Ti_{5c} rows

appear as bright stripes, while the bridging oxygen rows give a lower apparent height (22, 23, 31). Clean, well-ordered terraces with a low defect concentration are typically prepared by repeated cycles of Ar^+ sputtering and annealing in oxygen under ultrahigh vacuum (UHV), as described in Chapter 3 (32). Under increasingly reducing conditions, higher annealing temperatures or more aggressive sputtering, the surface develops the well-known (1×2) reconstruction, which shows a doubled periodicity and a distinct STM contrast and is commonly described in terms of added TiO_x rows. Oxygen vacancies are the most common intrinsic defects on rutile (110). They form preferentially at bridging oxygen sites and introduce localized Ti^{3+} states within the band gap. In STM images these vacancies appear as bright features between neighboring Ti_{5c} rows and frequently act as reactive centers for adsorption, dissociation and charge trapping (32, 33).

Anatase $\text{TiO}_2(101)$, by contrast, presents a distinct surface geometry and defective sites distribution. The unreconstructed (1×1) surface consists of alternating rows of undercoordinated titanium and oxygen atoms, in which fivefold coordinated Ti sites are periodically separated by bridging twofold coordinated oxygen atoms. This arrangement leads to a corrugated surface morphology that manifests as a characteristic sawtooth contrast in scanning tunnelling microscopy images (34–36). Clean anatase (101) terraces are obtained by gentler sputtering and annealing procedures than those used for rutile, all the preparation procedures are specified in Chapter 3. Unlike rutile (110), where oxygen vacancies are relatively stable at the surface, vacancies generated on anatase (101) tend to diffuse into subsurface layers and form Ti^{3+} centers beneath the topmost $\text{Ti}_{5c}\text{-O}_{2c}$ rows. This subsurface localization has been confirmed experimentally and significantly influences the interaction of anatase (101) with water, oxygen and other adsorbates (37).

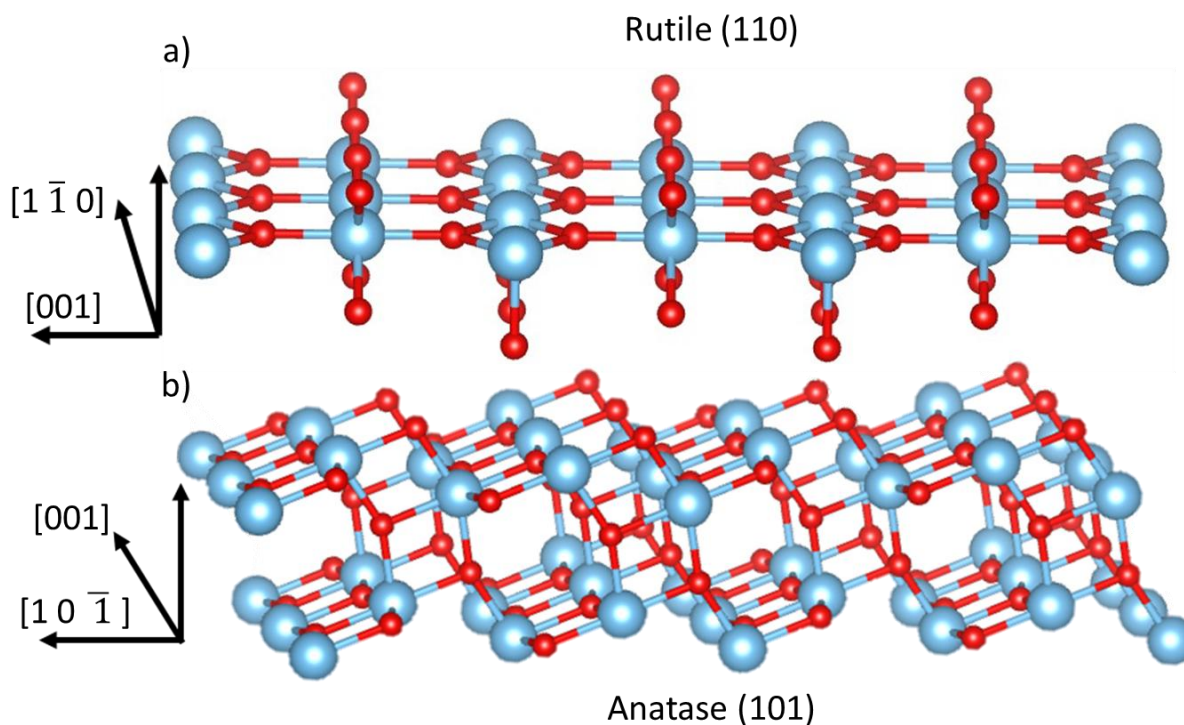


Figure 2.2.1. Ball-and-stick representation of the Rutile (110) and Anatase (101) unreconstructed, defect free surfaces. Models were generated using VESTA. Ti atoms in blue and O in red.

Because oxygen vacancies in anatase preferentially reside below the surface, step edges and other undercoordinated sites become the main reactive centers. These step sites host undercoordinated titanium atoms that appear as brighter, irregular features interrupting the otherwise regular zig-zag pattern in STM images (34). As will be shown in Chapters 5 and 6, such step edges provide undercoordinated sites that can dominate adsorption of molecules on anatase (101). A ball-and-stick representation of the ideal rutile (110) and anatase (101) terminations used as model surfaces in this work is presented in Figure 2.2.1.

2.3 Amino Acids and Their Interaction with TiO₂ Surfaces

Amino acids constitute the small organic units from which proteins are assembled. Their interaction with inorganic surfaces is largely determined by three functional groups: the amine (NH₂/NH₃⁺), the carboxylate (COOH/COO⁻), and the side chain, whose polarity and size differ from one amino acid to another. These groups can engage in several binding geometries, such as coordination to surface Ti sites, hydrogen bonding to surface oxygen or hydroxyl species, and longer range electrostatic interactions (38–42). Their protonation state further complicates their chemistry, as amino acids can adopt neutral, deprotonated, or zwitterionic forms depending on pH and local environment, an aspect that has been shown to strongly influence adsorption on metal oxide surfaces (43, 44).

Understanding amino acid adsorption on TiO₂ benefits from studies on simpler molecules, especially monocarboxylic acids. These molecules are useful model systems for amino acids because they share the same carboxylic group. On rutile TiO₂(110), carboxylic acids deprotonate and bind in a bridging bidentate (O,O) mode, a configuration stabilized by the Ti-Ti spacing of ~2.96 Å, which closely matches the carboxylate O···O distance. This geometry has been confirmed across a wide range of acidic adsorbates, from formic and acetic acid to benzoic and terephthalic acid, using techniques such as STM, IRRAS, and NEXAFS (45–47).

On anatase TiO₂(101), the situation is less uniform and a wider set of adsorption geometries has been reported. Its wider Ti-Ti separation (~3.79 Å) disrupt the ideal arrangement needed for symmetric (O,O) bridging, leading instead to more asymmetric or hydrogen bond stabilized configurations. High resolution STM and vibrational spectroscopy studies have shown that carboxylates on anatase (101) can adopt both monodentate and bidentate forms depending on

temperature, coverage, and the presence of surface hydroxyls (48). For example, acetic acid has been observed to form monodentate and bidentate on anatase (101) (49). Furthermore, O'Connor and co-workers (50) demonstrated that small changes in molecular structure can significantly alter adsorption modes on anatase (101), highlighting the sensitivity of this surface to local bonding environments. In addition, studies such as those by Petrik and co-workers have revealed that formic acid undergoes temperature dependent conversion from monodentate to bidentate on anatase (101) that have no direct analogue on rutile (51).

Compared to small carboxylic acids, amino acids introduce an additional level of complexity in adsorption studies because they contain multiple functional groups capable of interacting with oxide surfaces. Depending on the local chemical environment, these molecules can adopt different protonation states and bind to surface sites through several possible combinations of functional groups. To describe these adsorption geometries in a way throughout this work, a unified nomenclature is introduced and summarized in Figure 2.3.1. The figure is adopted from the manuscript: Adsorption and Sulphur-Selective Photooxidation of Cysteine on Anatase $\text{TiO}_2(101)$.

In this scheme, the adsorption configuration is defined by two elements. First, the protonation state of the molecule is indicated: molecular (M), zwitterionic (ZW), deprotonated at the carboxyl group DP_{COOH} deprotonated at the thiol group DP_{SH} , or bideprotonated biDP, where two functional groups lose a proton. Second, the atoms of cysteine involved in bonding with the TiO_2 surface are specified in parentheses. For example, labels such as (O,O), (O,N), or (O,S) indicate that the molecule coordinates to surface Ti atoms through these respective pairs of atoms. This notation therefore captures both the chemical state of the molecule and the specific surface coordination

motif. As illustrated in Figure 2.3.1, all configurations considered involve at least two interactions with surface atoms.

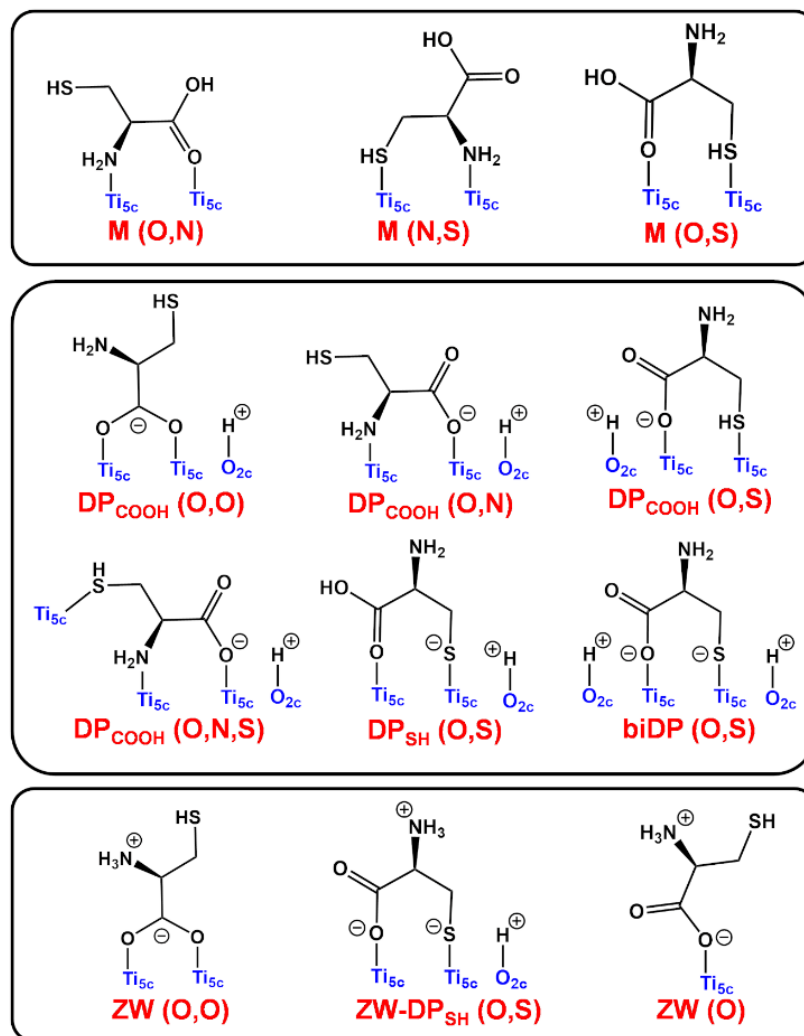


Figure 2.3.1. Nomenclature used in this work to describe protonation states and adsorption configurations of amino acids on TiO_2 surfaces. Protonation states include molecular (M), zwitterionic (ZW), deprotonated species (e.g., DP_{COOH} , DP_{SH} , and bideprotonated (biDP)). The atoms involved in surface bonding are indicated in parentheses, for example (O,O), (O,N), or (O,S). Taken from manuscript: *Adsorption and Sulphur-Selective Photooxidation of Cysteine on Anatase $\text{TiO}_2(101)$* in Chapter 5.

2.3.1 Cysteine Adsorption on Rutile (110) and Anatase (101) Surfaces

Cysteine is a sulfur containing amino acid whose redox active thiol group participates in biological processes such as protein folding (18) and cellular redox signaling (52). The only experimental

studies on cysteine adsorption on rutile $\text{TiO}_2(110)$ were conducted by Ataman and co-workers (53, 54), who reported that cysteine binds primarily through its carboxylate group in a bridging (O,O) configuration. This configuration was confirmed in the oxygen (O 1s) region of XPS spectra, which indicated that the molecule deprotonates during adsorption. Ataman et al. also observed that under standard conditions, cysteine maintains its NH_2 group neutral. However, at higher surface coverages, at liquid nitrogen temperatures, zwitterionic forms of cysteine were detected, with the protonated NH_3^+ group clearly observed in the N1s peak. Regarding sulphur interactions, they identified two species, one belonging to the intact thiol group and a second low binding energy feature. They suggested that this feature indicated S-Ti bonding, coming from the cleavage of the C-S bond at an oxygen vacancy site. However, theoretical studies have largely refuted this interpretation, as cysteine was found to be stable when adsorbed onto rutile (110), with no indication of C-S bond breaking.

Muir and Idriss (55) found that the most stable adsorption configuration for cysteine on rutile (110) is also a (O,O) bidentate binding mode, using DFT calculations. Their study (shown in Figure 2.3.1.1) calculated various adsorption modes and provided energy values for each structure. The most stable configuration, structure 1 (bridging bidentate (O,O)), had an adsorption energy of -1.47 eV per molecule, followed by structure 8, which corresponds to a bridging (O,N) mode, with an energy of -1.39 eV. Other stable configurations, such as 2, 3, 4, and 9, exhibited similar energy values, but all were (O,O) or (O,N), with minor variations from the most stable configurations. In contrast to Ataman's experimental findings, DFT studies confirmed that cysteine remains stable on rutile $\text{TiO}_2(110)$ and does not undergo C-S bond cleavage. Although some structures predicted sulphur to be directly bonded to titanium, such as structures 10, 11, and 12, they were found to be

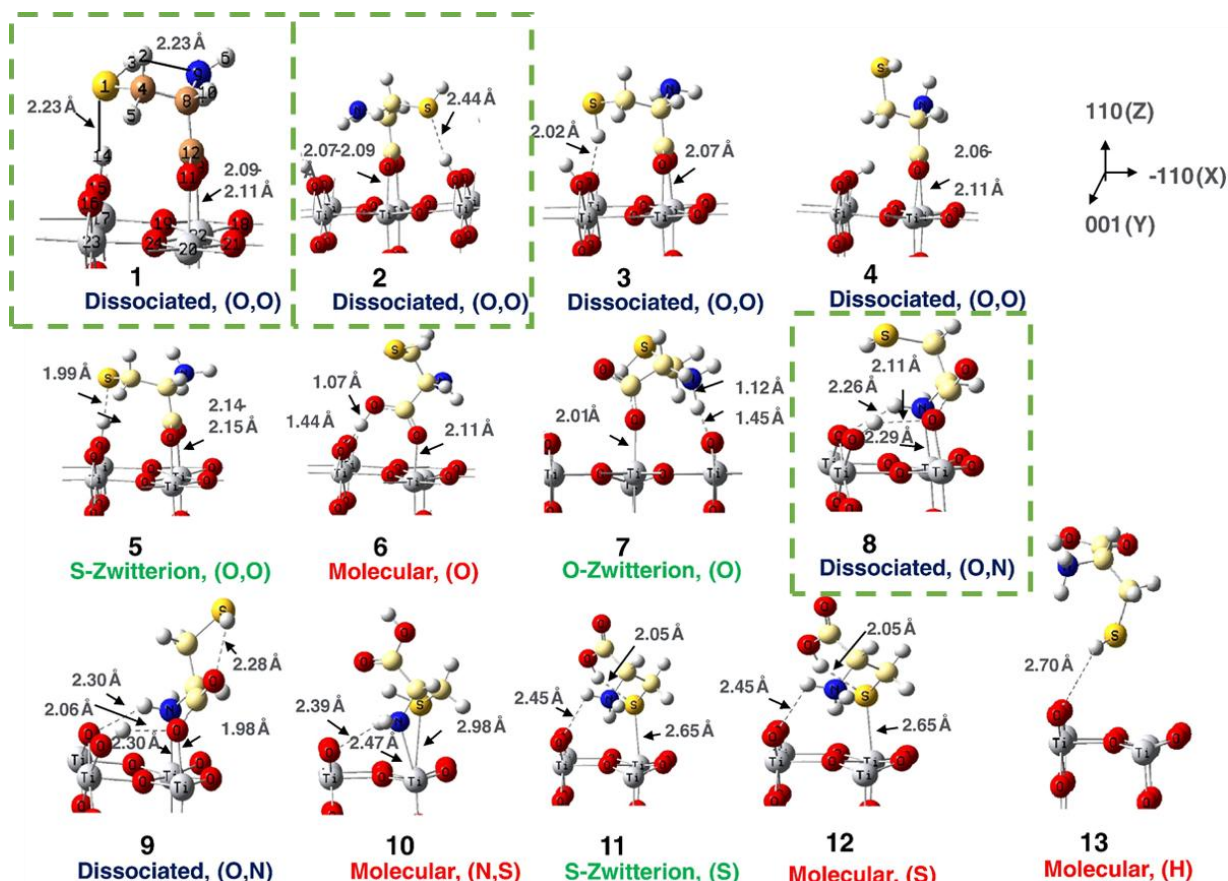


Figure 2.3.1.1 Cysteine adsorption geometries on rutile (110) as calculated by Muir and Idriss (55). The dotted green squares mark the most stable geometries. (Images of 13 different adsorption configurations are shown, with sulphur (S) in yellow, carbon (C) in brown, nitrogen (N) in blue, hydrogen (H) in white, oxygen (O) in red, and titanium (Ti) in gray. Letters in parentheses indicate the atoms involved in the main adsorption. S-Zwitterion indicates proton transfer between the SH and NH₂ groups, while O-Zwitterion indicates proton transfer between the SH and COOH groups.

significantly less stable, with adsorption energies of -0.71 eV, -0.50 eV, and -0.91 eV, respectively.

This discrepancy raises the question of the origin of the low energy S 2p peak observed in XPS.

Pantaleone et al. (56, 57) further supported this theory with their calculations, confirming that the most stable configuration on rutile(110) does not involve sulphur directly interacting with titanium. Their results, shown in Figure 2.3.1.2a, revealed that the most stable geometry is a bridging bidentate (O,O), although with different hydrogen bonding interactions than previously observed. They also found that the zwitterionic form of cysteine is stable, contrary to the findings of Muir and Idriss, who did not consider this form stable. Thus, a discrepancy exists between experimental

observations and theoretical models, which is addressed here through a direct comparison of several experimental techniques and DFT calculations.

At the time of writing and to the best of our knowledge based on the cited literature, cysteine adsorption on anatase $\text{TiO}_2(101)$ has not been characterized experimentally. However, theoretical studies predicted distinct adsorption modes due to the differences in surface geometry between anatase (101) and rutile (110). Pantaleone et al. found that anatase (101), with its wider Ti-Ti spacing, favors the (O,N) binding mode for cysteine compared to rutile (110), which is stabilized by hydrogen bonding and thiol interactions (Figure 2.3.1.2b). In contrast, rutile (110) favors the (O,O) configuration, as previously discussed. These predictions were experimentally tested using STM, XPS, and FT-IRRAS, confirming that cysteine adsorbs on anatase (101) in a way that differs significantly from rutile (110) (Chapter 5).

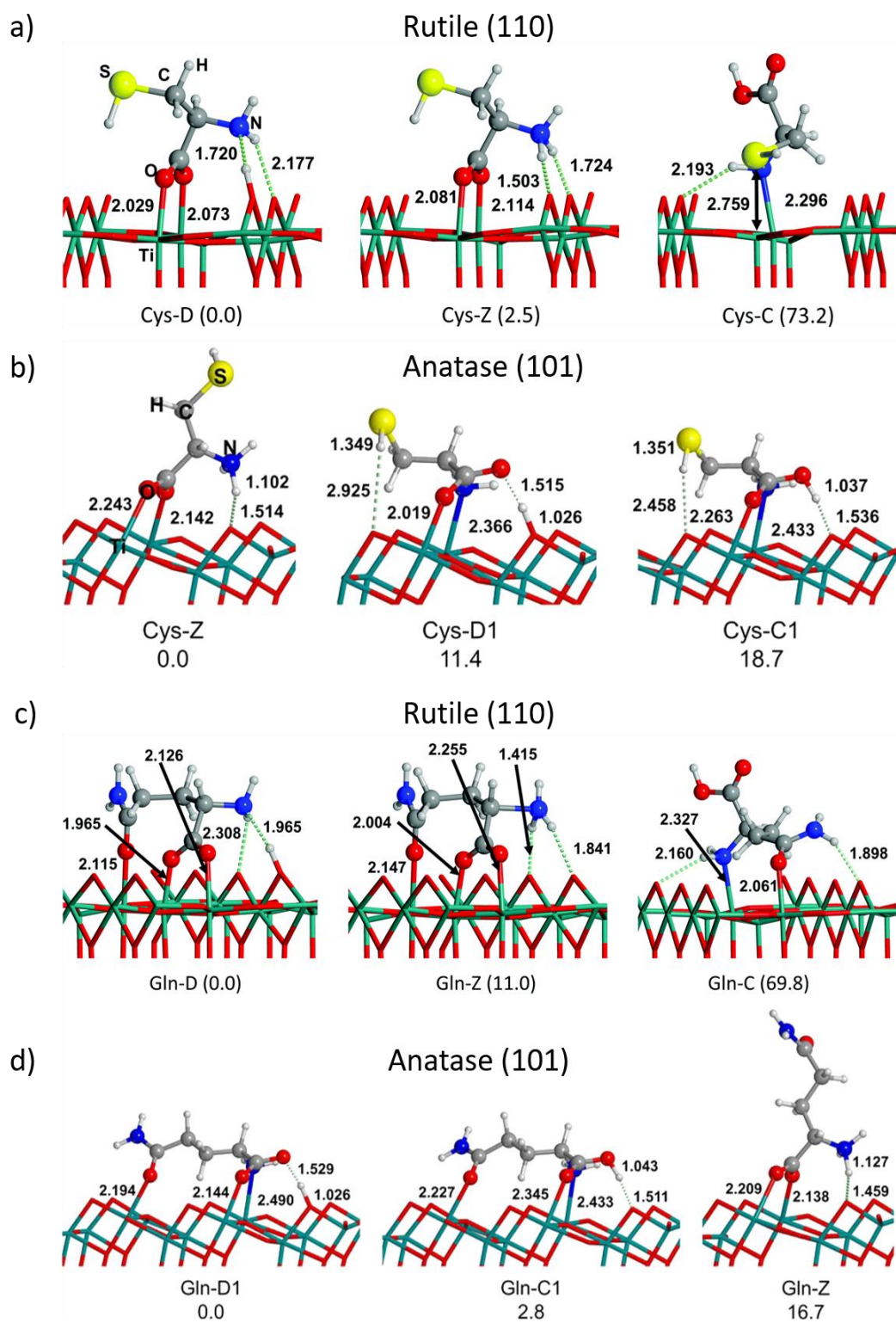


Figure 2.3.1.2. PBE-D2* optimized geometries for (a) Cysteine on Rutile (110), (b) Cysteine on Anatase (101), (c) Glutamine on Rutile (110), (d) Glutamine on Anatase (101). Bond distances are in Å. Relative energy values are given in kJ/mol. Taken from references (56, 57).

2.3.2 Asparagine adsorption on Rutile (110) and Anatase (101) Surfaces

In contrast to cysteine, the adsorption of L-asparagine on TiO₂ surfaces had not been explored experimentally or theoretically prior to this work. Asparagine carries a polar amide side chain that does not undergo redox transformations under mild conditions, making it a useful counterpart to cysteine for studying non redox driven interactions on oxide surfaces. Some observations about the possible adsorption geometries, however, can be drawn from studies of related amino acids.

In particular, DFT calculations for glutamine adsorption indicate that anatase (101) tends to stabilize mixed (O,N) coordination geometries better than rutile (110). As illustrated in Figures 2.3.1.2 c and d, this preference originates from the larger lateral Ti-Ti spacing on anatase and the higher availability of undercoordinated surface sites, which allow the molecule to adopt more flexible binding geometries involving both the carboxylate and amide functionalities. On rutile (110), the more constrained surface geometry limits such configurations, favoring simpler coordination motifs. (44, 56). Because glutamine possesses a longer side chain than asparagine and can extend across multiple Ti rows, some of the adsorption geometries shown in Figure 2.3.1.2d are sterically inaccessible for asparagine (Gln-D1 and Gln-C1).

Additional information comes from studies of asparagine and related amino acids on metal substrates. STM measurements on Cu(111) revealed that asparagine adsorbs in a deprotonated form but does not form ordered superstructures, unlike non-polar amino acids such as leucine or glycine (58) . Electrochemical studies on gold similarly showed that adsorption proceeds through both the deprotonated carboxylate and the amide carbonyl group, indicating that the side chain actively participates in binding (59). Additional information comes from closely related amino acids. Experimentally, XPS and near edge X-ray absorption fine structure spectra (NEXAFS) of

glutamic acid on rutile (110) indeed confirmed dominant carboxylate anchoring with a coexistence of deprotonated and zwitterionic species (38).

Chapter 5 of this thesis presents the first experimental investigation of asparagine adsorption on both rutile(110) and anatase(101). Using STM, XPS, and FT-IRRAS, we show that asparagine binds through its carboxylate group in a bridging (O,O) configuration on rutile, whereas on anatase the molecule adopts a combination of (O,N) and monodentate geometries. These results reveal a clear facet dependence and extend our understanding of how amide containing amino acids interact with TiO₂ surfaces, an essential step toward predicting biomolecular behaviour at photoactive oxide interfaces.

2.4 Mechanisms of Cysteine Oxidation on TiO₂

In proteins, cysteine residues act as redox sensitive sites that can respond to changes in the local oxidative environment. The thiol group (-SH) is one of the most reactive functional groups in proteins and can be converted into a series of oxidized forms, including sulfenic (-SOH), sulfinic (-SO₂H) and sulfonic (-SO₃H) acids (18, 52, 60). These post-translational modifications can be reversible or irreversible and are involved in processes such as redox signaling, protein folding and the cellular response to oxidative stress (61, 62). A schematic overview of the main cysteine oxidation pathways in biological systems is shown in Figure 2.4.1 taken from reference (60).

This chemistry becomes especially relevant when considering TiO₂, a widely studied photocatalyst known for generating ROS under UV illumination. As shown in Figure 2.4.2, the band structure

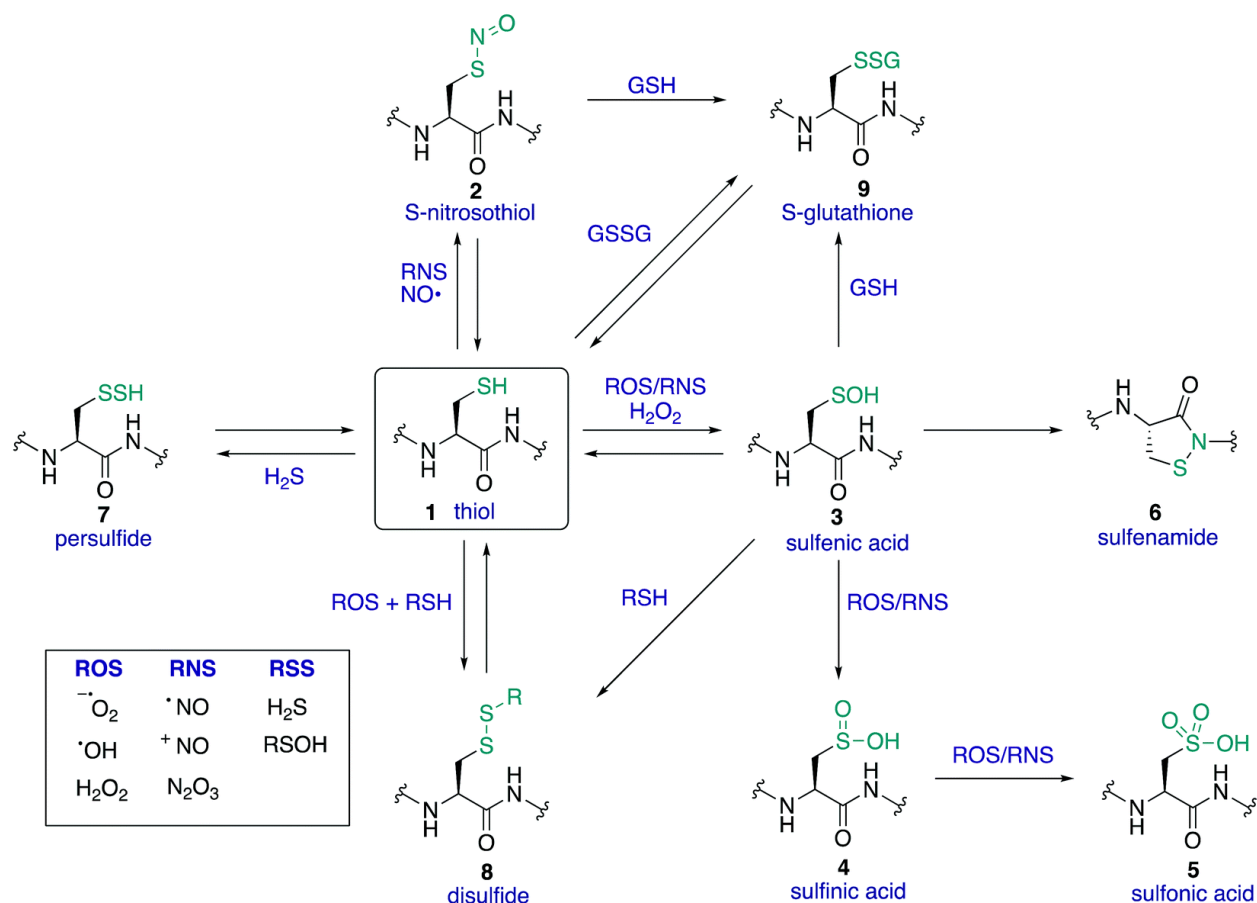


Figure 2.4.1. Overview of major cysteine oxidation pathways in biological systems, illustrating the conversion of thiol groups into sulfenic, sulfinic, and sulfonic acid species, as well as disulfide bond formation. These post-translational modifications differ in reversibility and impact protein structure and function. Taken from reference (60)

of TiO_2 places the conduction band (CB) around +0.2 to +0.3 V vs SHE (standard hydrogen electrode) and the valence band (VB) around -2.7 to -3.0 V, with a bandgap of approximately 3.0-3.2 eV (5, 6, 63). Upon UV excitation, photogenerated electrons in the CB reduce molecular oxygen to superoxide, while holes in the VB oxidize water or surface hydroxyls to produce hydroxyl radicals. Although exact band positions depend on pH, crystallinity, and surface termination, there is broad consensus that TiO_2 consistently generates both superoxide and hydroxyl radicals under UV irradiation (26, 29, 64, 65).

The mechanisms discussed here are directly relevant for interpreting the oxidation pathways observed experimentally in later chapters. They link the intrinsic redox chemistry of cysteine with

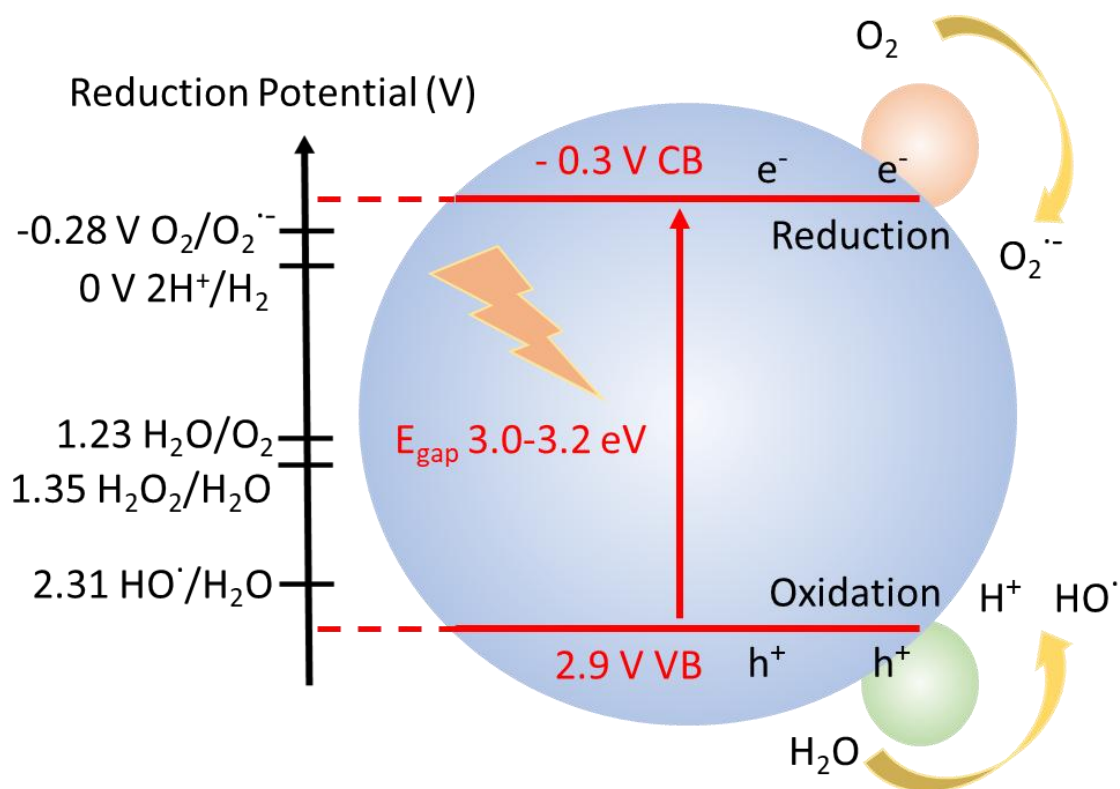


Figure 2.4.2 can be defined as the flux. Simplified band diagram of TiO₂ under UV irradiation, showing the valence band (VB) and conduction band (CB) positions relative to the standard hydrogen electrode (SHE). Data reconstructed from References (26, 29, 64).

the photocatalytic properties of TiO₂ surfaces and provide the building ground for understanding how biomolecules respond to photoactive environments. Further details are provided in the introductions to Chapters 4, 5 and 6 and in the manuscript introductions.

3: Theoretical Background of the Techniques Used

3.1 Sample Preparation Methods

In surface science we normally work under ultra-high vacuum (UHV), because at higher pressures the sample is contaminated on the timescale of the experiment. Even a small residual gas pressure introduces adsorbates that quickly mask the intrinsic structure and chemistry of the surface. At UHV pressures the adsorption rate is slow enough that we can keep a reasonably clean surface for several hours. This behaviour can be rationalized in the molecular flow regime using the mean free path λ , i.e. the average distance a molecule travels between collisions (66).

$$\lambda = \frac{k_B T}{\sqrt{2} \pi d^2 P} \quad (\text{Eq. 1})$$

where k_B is Boltzmann's constant, T the absolute temperature, d the effective molecular diameter, and P the pressure. At a pressure in the order of 10^{-10} mbar (10^{-8} Pa), λ is in the order of 10^3 km, for typical residual gases, so gas-gas collisions inside the chamber are negligible and molecules predominantly interact with chamber walls or the sample surface. The number of molecules colliding on a unit of surface area can be defined as the flux and is expressed as:

$$J = \frac{P}{\sqrt{2 \pi m k_B T}} \quad (\text{Eq. 2})$$

The time needed to form a full monolayer of adsorbates is given by:

$$\tau = \frac{N_{ML}}{S_c J} \quad (\text{Eq. 3})$$

Where N_{ML} is the density of molecules per monolayer and S_c is the sticking coefficient. Using a conservative assumption and assuming a sticking coefficient of one, $T = 300$ K, $P = 10^{-10}$ mbar,

using H₂O ($m = 18$) and a density of molecules per monolayer of 10^{15} molecules/cm² the time needed to form a monolayer is around 8 hours, time enough to perform our experiments.

In the UHV systems used at DESY NanoLab (67), the pressure is reduced in several stages. Roughing and turbomolecular pumps first bring the chambers into the high vacuum regime, after which a combination of titanium sublimation and ion getter pumps is used to reach base pressures in the 10^{-10} - 10^{-11} mbar range. During titanium sublimation, the filaments are briefly heated to about 45 A to deposit a fresh Ti film on selected parts of the chamber walls. This film chemisorbs reactive residual gases such as CO, CO₂ and O₂, thereby reducing their partial pressures. The ion pump operates continuously, maintaining a Penning discharge at approximately 6 kV (varies depending on the chamber) and trapping the resulting ions in titanium cathodes. The pressure is monitored with a cold cathode gauge based on an inverted magnetron design, which is robust against accidental venting and therefore well suited for continuous long term operation (68).

3.1.1 Sample Preparation:

Clean and well-ordered TiO₂ single-crystal surfaces were mounted on a Molybdenum sample plate and prepared by repeated cycles of argon-ion sputtering and thermal annealing (see figure 3.1.2b). Sputtering removes surface contaminants and the outermost atomic layers by momentum transfer from Ar⁺ ions, while annealing restores the long range order of the crystal lattice. For rutile TiO₂(110), each cleaning cycle consisted of sputtering at 1 keV (5 min, $\sim 10^{-6}$ mbar Ar) followed by annealing at 1200 K on the molybdenum sample plate: first for 10 min in 10^{-7} mbar O₂, then for 10 min under UHV. Anatase TiO₂(101) samples were treated in a similar way, but annealed only at 700 K in O₂ (10^{-7} mbar, 10 min) and then at 950 K, to avoid phase transitioning into rutile,

under UHV for 10 min. Typically, 5-10 such cycles were required to obtain well-ordered, contamination free surfaces, in line with previous reports on rutile (110) and anatase (101) preparation (32, 37). Sample temperatures were calibrated for our specific chambers and monitored in real time with a pyrometer focused on the molybdenum plate supporting the crystals.

After each preparation cycle, surface order and cleanliness were checked by Low Energy Electron Diffraction (LEED). Electrons in the 20-300 eV range have wavelengths comparable to interatomic distances and mean free paths below 1 nm, which makes LEED highly surface-sensitive (69). Clean rutile (110) and anatase (101) surfaces produced sharp (1×1) diffraction patterns without extra spots or streaks, indicating long range order and the absence of reconstructions or adsorbates within the detection limit. Figure 3.1.1 shows the representative LEED patterns of freshly prepared rutile (110) and anatase (101).

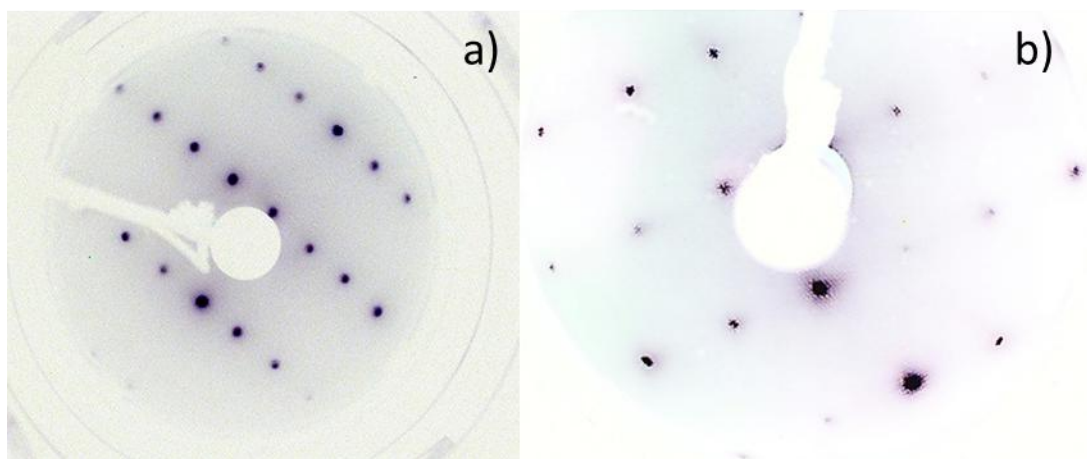


Figure 3.1.1. Low-energy electron diffraction (LEED) patterns of clean and ordered TiO_2 surfaces: (a) rutile (110) and (b) anatase (101), both measured at 100 eV. The sharp (1×1) diffraction spots indicate long-range surface order and the absence of surface reconstructions.

Deposition of cysteine and asparagine was performed by sublimation under UHV. The powdered amino acids were loaded into a glass dosing tube connected to an independent gas line equipped with its own turbomolecular pump. The tube was resistively heated with external heating bands, while a type-K thermocouple in direct contact with the glass provided temperature control.

Sublimation occurred reproducibly at approximately 410 K without visible decomposition (53, 70). The resulting vapor flux was introduced into the preparation chamber through a leak valve, which allowed precise control of the exposure. Typically, the dosing is done at a pressure between 10^{-6} and 10^{-7} mbar with the exposure controlled by the dosing time. Because the gas line was pumped independently of the main chamber, only amino acid vapor, rather than contaminants from the pumping system, reached the TiO_2 surface. A photograph of the dosing setup used for these experiments is shown in Figure 3.1.2a.

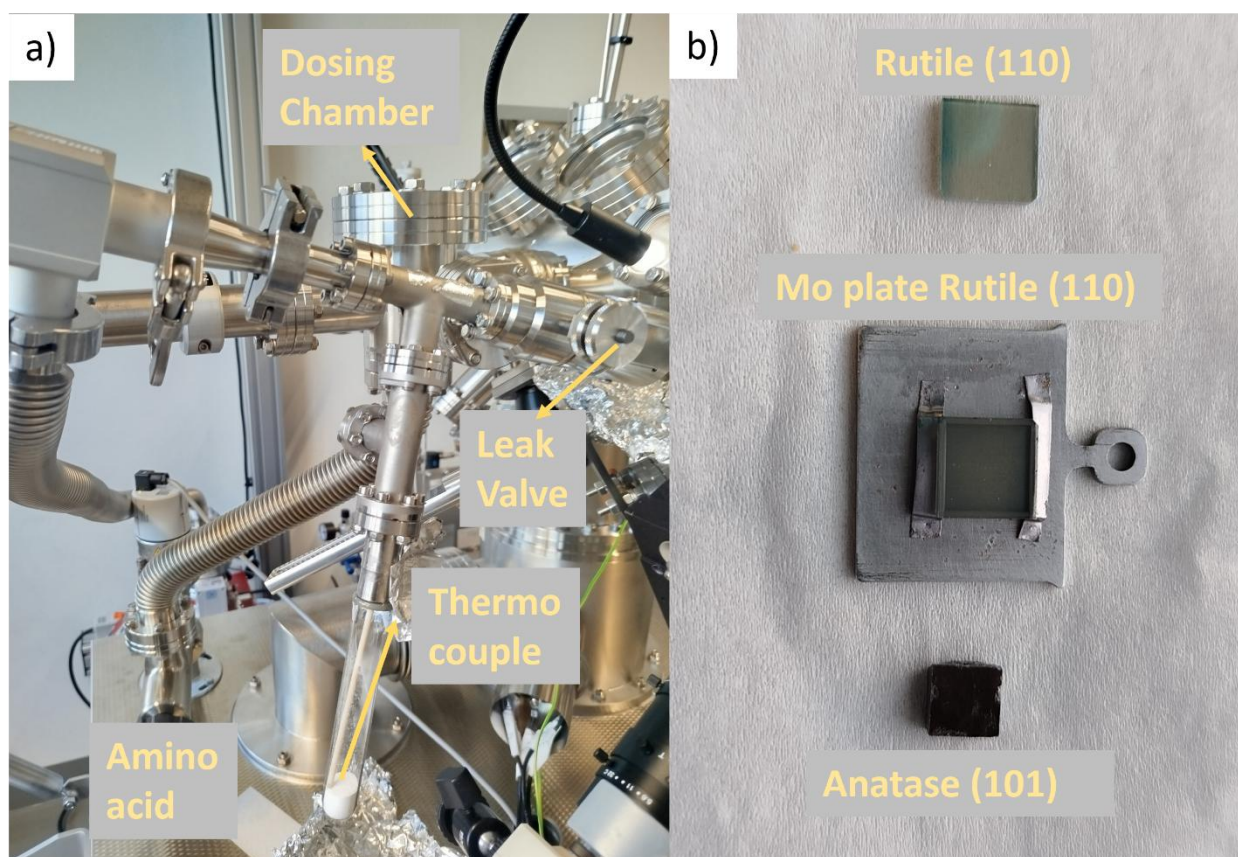


Figure 3.1.2. a) Photograph of the dedicated gas line used for amino acid sublimation under ultrahigh vacuum conditions. The independently pumped dosing line enables controlled evaporation of cysteine and asparagine while minimizing contamination of the main chamber. b) photograph of a rutile (110) crystal, a rutile (110) crystal mounted on a Molybdenum sample holder plate and an anatase (101) crystal.

Dataset specific preparation and dosing parameters are provided in Appendices 1-3 (Supplementary Information of the corresponding manuscripts).

All experiments were performed at DESY NanoLab (Centre for X-ray and Nano Science, DESY, Hamburg (67)). The laboratory consists of a multi chamber UHV infrastructure connected by a dedicated transfer line (UHV tunnel) with a base pressure of 10^{-9} mbar, enabling sample transfer between preparation and analysis chambers without breaking vacuum. In this thesis, measurements were carried out using the XPS, STM and FT-IRRAS measuring stations. Sample preparation and LEED was done in molecular beam epitaxy chambers.

3.2 Introduction to Spectroscopical Techniques

Spectroscopic methods rely on the fact that atoms and molecules occupy discrete energy levels and interact with radiation only when its energy matches the difference between those levels. The associated absorption, emission or scattering processes generate characteristic spectra that carry information about composition, bonding and the local chemical environment (71).

The development of spectroscopy has been closely linked to advances in optics and quantum theory. Early observations of discrete line spectra contributed to the development of quantum mechanics, and modern laser and synchrotron sources have greatly extended the accessible energy range while improving sensitivity and resolution. As a result, spectroscopic techniques are now standard tools across chemistry, physics and materials science (72).

In this work, we rely mainly on two complementary methods. X-ray photoelectron spectroscopy (XPS) provides elemental and chemical state information from the first few atomic layers of the surface which makes it well suited to follow adsorption, deprotonation and redox processes. Fourier-transform infrared reflection-absorption spectroscopy (FT-IRRAS) probes vibrational modes of molecules adsorbed on metal-oxide surfaces and is particularly sensitive to binding geometry and molecular orientation. Used together, XPS and FT-IRRAS provide a consistent picture of how amino acids interact with TiO_2 and how their bonding evolves during adsorption and photocatalytic reaction.

3.3 X-Ray Photoelectron Spectroscopy: XPS

X-ray photoelectron spectroscopy (XPS) is one of the most widely used techniques for surface characterization. Since its development in the 1960s by Siegbahn et al., work that was later recognized with the Nobel Prize in Physics in 1981, XPS has become an essential tool for identifying elements and their chemical states at solid surfaces (73). The method is based on the photoelectric effect: monochromatic X-rays eject core level electrons from the sample, and from the kinetic energy distribution of these photoelectrons one can determine their binding energies and obtain information about the electronic structure (74). Because electrons lose energy rapidly when travelling through solids, only those generated within a few nanometers of the surface can escape without undergoing inelastic scattering. As a result, XPS is intrinsically surface sensitive, probing roughly the first 5-10 atomic layers. Beyond elemental identification, XPS provides useful observation about oxidation states, chemical bonding and the local electronic environment through features such as chemical shifts, spin orbit splitting and multiplet structures, enabling, for example, the distinction between Ti^{3+} and Ti^{4+} species in titanium oxides or between different functional groups in organic adsorbates (75).

3.3.1 Theoretical Background and Principles

XPS is based on the photoelectric effect, first explained by Einstein in 1905. When a photon of energy $h\nu$ is absorbed by a solid, it can transfer energy to an electron in a core level. If the photon energy exceeds the binding energy of that electron, the electron is emitted into the vacuum. Energy conservation for this process can be expressed as:

$$E_{kin} = h\nu - E_{bin} - \varphi \quad (\text{Eq. 4})$$

The binding energy E_{bin} represents the energy required to remove an electron from its initial orbital to the Fermi level, conventionally set as zero on the XPS binding energy scale. The work function ϕ is defined as the minimum energy needed to remove an electron from the Fermi level to the vacuum level (75, 76).

The probability that a given core level contributes to the photoelectron signal depends on its photoionization cross-section, which varies with photon energy and with the angular momentum of the orbital. In practice, tabulated sensitivity factors derived from these cross-sections are used to compare peak areas and to estimate relative elemental concentrations (77).

When a conducting sample is electrically connected to the spectrometer, their Fermi levels align at equilibrium, but their vacuum levels generally do not coincide. As a consequence, electrons emitted from the sample experience an energy shift when they enter the spectrometer. This shift is associated with the contact potential between the sample and the analyzer, $\phi_{\text{sample}} \pm \phi_{\text{spectrometer}}$.

- If $\phi_{\text{sample}} > \phi_{\text{spectrometer}}$, electrons gain kinetic energy upon entering the spectrometer.
- If $\phi_{\text{sample}} < \phi_{\text{spectrometer}}$, electrons lose kinetic energy upon entering the spectrometer.

Thus, the kinetic energy measured inside the spectrometer must include this shift. Initially, the photoelectron energy can be written as:

$$Ek(\text{initial}) = h\nu - EB - \phi_{\text{sample}} \quad (\text{Eq. 5})$$

but the spectrometer records it as:

$$Ek(\text{measured}) = h\nu - EB - \phi_{\text{spectrometer}} \quad (\text{Eq. 6})$$

This correction ensures that all binding energies reported by the spectrometer are referenced to a common energy scale, independent of variations in the sample work function, and allows reliable comparison between different materials (75–77). The situation is illustrated schematically in Figure 3.3.1.1.

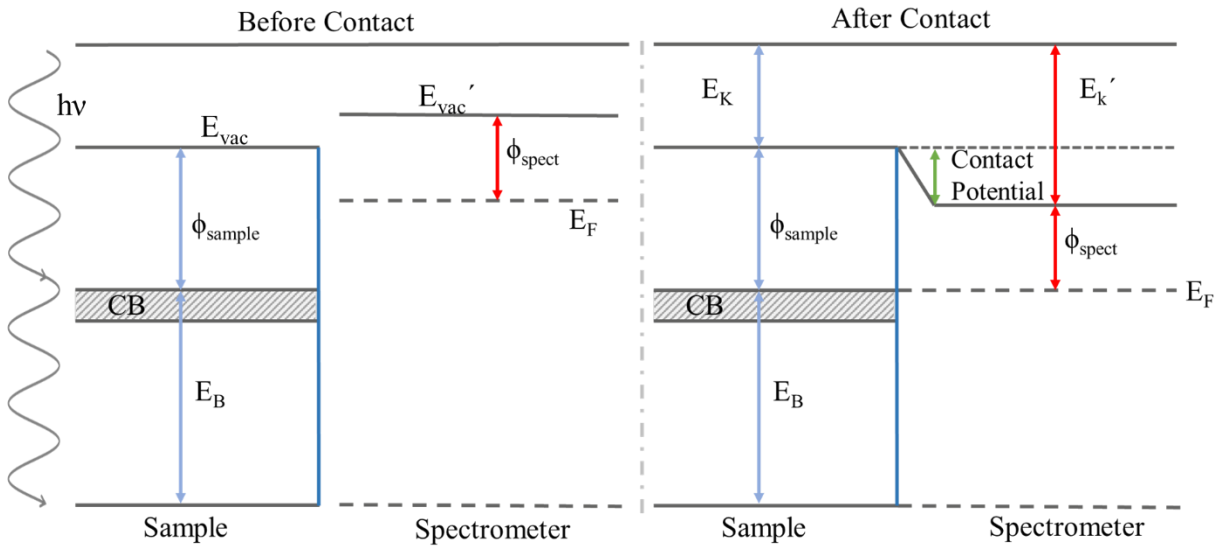


Figure 3.3.1.1. Schematic energy level diagram showing the alignment of Fermi levels and vacuum levels before and after electrical contact between sample and spectrometer. The contact potential and resulting energy shift experienced by photoelectrons are indicated.

The surface sensitivity of XPS originates from the limited inelastic mean free path (IMFP) of electrons in solids. The IMFP (λ) is the average distance an electron travels before losing energy through inelastic processes such as plasmon excitation or electron-electron scattering. Only electrons that reach the surface without inelastic loss contribute to the photoelectron peaks; inelastically scattered electrons form the underlying background (78).

The effective information depth d is the depth from which most of the detected signal originates, is approximately three times the IMFP:

$$d \approx 3 * \lambda * \cos(\theta) \quad (\text{Eq. 7})$$

where θ is the emission angle relative to the surface normal. For normal emission $\theta = 0^\circ$ more than 95% of the detected signal originates from within three IMFPs of the surface. By increasing the emission angle towards grazing emission, the effective sampling depth decreases further and the surface sensitivity is enhanced. For Al $K\alpha$ radiation, most photoelectrons have kinetic energies of 200-1200 eV, corresponding to information depths of roughly 2-10 nm. Figure 3.3.1.2 shows the dependence of the IMFP on kinetic energy for different materials (78).

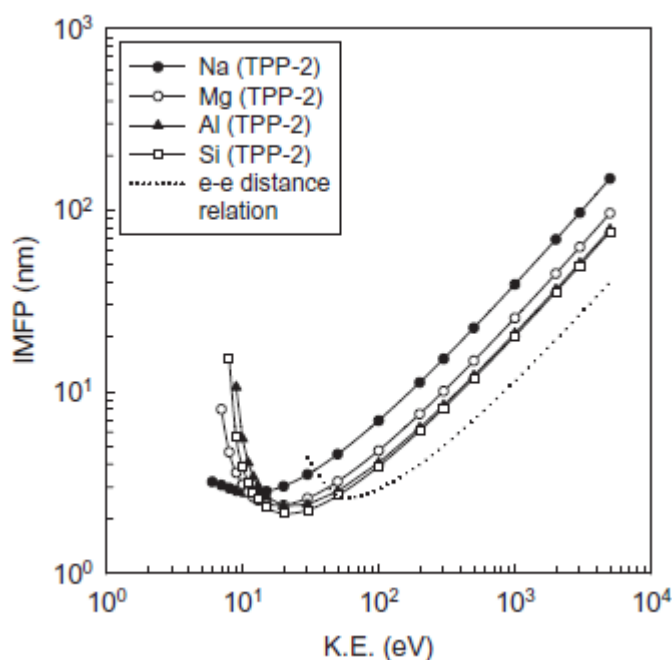


Figure 3.3.1.2. Dependence of the inelastic mean free path of electrons on kinetic energy for selected elements, illustrating the surface sensitivity of XPS in the typical photoelectron energy range. Adapted from (78).

3.3.2 Detection Principles

Laboratory XPS systems most commonly use Al $K\alpha$ (1486.6 eV) and Mg $K\alpha$ (1253.6 eV) X-ray sources generated by bombarding a metal anode with high-energy electrons. These photon energies are high enough to excite core levels of most elements while keeping the inelastic mean free path short, which ensures intrinsic surface sensitivity. In modern instruments the characteristic emission

line is usually monochromated (e.g. with quartz or grating optics) and focused onto the sample. Monochromation improves energy resolution, suppresses Bremsstrahlung background and reduces sample damage, at the cost of a lower overall photon flux (72-74). In addition to conventional laboratory sources, synchrotron radiation provides intense, tunable and often polarized X-ray beams. This enables experiments such as resonant photoemission, angle-resolved studies and depth profiling that are not accessible with fixed-energy anodes. In the hard X-ray regime (HAXPES), higher photon energies increase the kinetic energy and inelastic mean free path of the emitted electrons, extending the probing depth from a few nanometres to several tens of nanometres and thus bridging surface and bulk sensitivity.

Electron kinetic energies are analyzed with electron energy analyzers, most commonly hemispherical analyzers (HSA). An HSA consists of two concentric hemispherical electrodes that create an electrostatic field, allowing only electrons with a selected kinetic energy to follow a stable trajectory between them. Electrons emitted from the sample are first collected and decelerated by an electrostatic lens system, which adjusts their energy to match the chosen pass energy E_{pass} of the analyzer. The spectrum is then recorded by varying the lens retardation potential so that electrons of different initial kinetic energies all enter the analyzer with the same E_{pass} . Electrons with slightly higher or lower energies deviate from the ideal path and do not reach the detector. The schematic of a XPS setup and the XPS setup of our laboratory is shown in Figure 3.3.2.1

The overall energy resolution is determined by a combination of the pass energy, the entrance/exit slit width and the quality of the electrostatic field. Lower pass energies and narrower slits yield higher resolution but reduce the count rate and thus increase acquisition times. In routine practice,

survey spectra are acquired at relatively high pass energies to maximize signal, whereas core level spectra are collected at lower pass energies to resolve chemical shifts and multiplet structures. Detection is usually achieved with a multichannel detector consisting of microchannel plates coupled to a phosphor screen and a position sensitive readout (e.g. CCD or CMOS camera). Such arrays allow simultaneous collection over a finite energy window and dramatically shorten acquisition times compared to single-channel detectors (72-74)

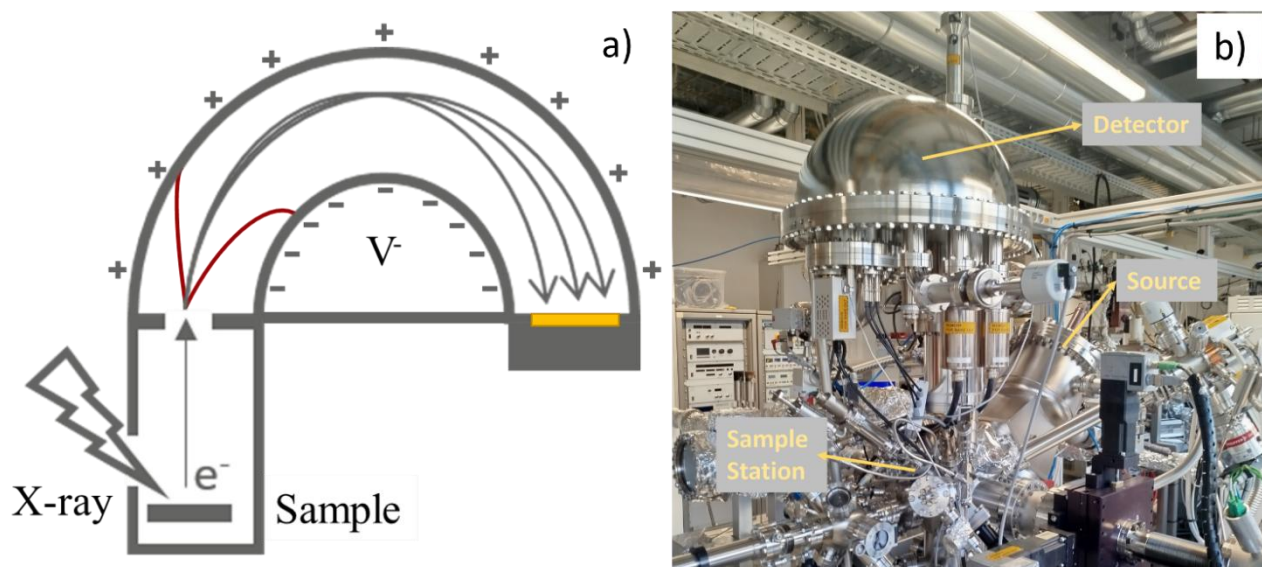


Figure 3.3.2.1. (a) Schematic representation of a hemispherical electron energy analyzer, illustrating the energy selection principle. (b) Photograph of the XPS setup used in this work at DESY Nanolab (67).

3.3.3 Interpretation of XPS Spectra

The XP spectra acquired in this work consist of well-defined core level peaks superimposed on an inelastic background. Since the objective is to determine adsorption geometries and chemical states of specific functional groups on $\text{TiO}_2(110)$ and $\text{TiO}_2(101)$, the fitting strategy was adapted to the spectral regions relevant for cysteine and asparagine, namely C 1s, O 1s, N 1s, S 2p and Ti 2p.

A key feature of XPS spectra is spin-orbit coupling which produces characteristic doublets in the spectra. Levels with orbital angular momentum $l > 0$ are split into two components.

$$j = l \pm \frac{1}{2} \quad (\text{Eq. 8})$$

For example, p-orbitals ($l=1$) split into $2p_{3/2}$ and $2p_{1/2}$, with an intensity ratio of 2:1 dictated by degeneracy (g).

$$g = 2j + 1 \quad (\text{Eq. 9})$$

In the present work, the S 2p region was always fitted as a constrained doublet with a fixed $2p_{3/2}:2p_{1/2}$ intensity ratio of 2:1, a fixed spin-orbit splitting of 1.2 eV, and identical full width at half maximum (FWHM) for both components. These constraints were imposed consistently in all fits and serve as an internal consistency check for sulphur chemical state assignment.

Another central concept in XPS interpretation is the chemical shift, which reflects how the local bonding environment modifies the electrostatic potential around an atom. Variations in oxidation state or coordination geometry led to systematic shifts in binding energy, allowing different chemical species of the same element to be distinguished. In this work, chemical shifts were used to differentiate, for example, distinct carbon species according to the electron affinity of the substituent group, to differentiate between protonated NH_3^+ and neutral NH_2 amino groups.

Peak widths also carry information. In addition to instrumental broadening (X-ray linewidth, analyzer resolution), intrinsic effects such as core-hole lifetime and local disorder contribute to the overall linewidth.

The natural linewidth caused by the finite lifetime of the core hole is described by a Lorentzian function:

$$L(E) = \left(\frac{1}{\pi}\right) * \frac{(0.5*\Gamma)}{(E - E_0)^2 + (0.5*\Gamma)^2} \quad (Eq. 10)$$

where E_0 is the peak position and Γ the full width at half maximum (FWHM).

Instrumental broadening follows a Gaussian distribution:

$$G(E) = \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{(E - E_0)^2}{2\sigma^2}} \quad (Eq. 11)$$

where σ is related to the Gaussian FWHM by $FWHM = 2\sqrt{2\ln 2} * \sigma$

In practice, XPS peaks are modeled with a Voigt profile, the convolution of Lorentzian and Gaussian functions:

$$V(E) = \int_{-\infty}^{\infty} G(E') * L(E - E') dE' \quad (Eq. 12)$$

Since this integral has no closed analytical form, most fitting routines employ a pseudo-Voigt function:

$$PV(E) = \eta L(E) + (1 - \eta)G(E) \quad (Eq. 13)$$

where η represents the relative Lorentzian/Gaussian contribution.

In the present work, peaks were fitted using a Gaussian-Lorentzian mixed function GL(30), corresponding to a pseudo-Voigt profile with 30% Lorentzian character and 70% Gaussian character. This line shape was found to adequately reproduce the experimental peak shapes of

molecular adsorbates on TiO₂ and was applied consistently across the fitted regions unless specific asymmetry in Ti 2p required minor adjustments.

Accurate fitting also requires an appropriate treatment of the inelastic background. XPS spectra invariably contain a background arising from electrons that have undergone one or more inelastic scattering events before escaping the solid. To isolate the true photoemission signal, this background must be subtracted or modelled during the fitting procedure. In this work, a Shirley background was employed. This model assumes that the background intensity beneath a peak is proportional to the integrated signal at higher binding energies. The Shirley approach provides a stable and physically reasonable description of the inelastic tail for the core level spectra analyzed here and was applied consistently to all fitted regions (79, 80).

3.3.4 Equipment and Experimental parameters

In this thesis, XPS measurements were carried out in a dedicated UHV system at DESY NanoLab (67) equipped with a Al K α source (1486 eV), model FOCUS 500 and a PHOIBOS 150 2D-DLD hemispherical analyzer both from SPECS with differential pumping mounted in a fixed geometry of 55° incidence angle. The analysis chamber reached a base pressure in the low 10⁻¹⁰ mbar range during measurements. Although the manipulator allows polar rotation and thus changing the emission angle unless otherwise stated is always 0° with respect of the surface normal. Survey spectra were acquired with a pass energy of 50 eV and an energy step of 0.5 eV, while high-resolution core level spectra were collected with a pass energy of 30 eV and an energy step of 0.1 eV. Binding energies were calibrated by referencing the Fermi edge of a clean metallic sample when calibrating the spectrometer and then using the adventitious C 1s signal at 284.8 eV (81, 82).

Peak fitting was done using CASA XPS (83). Peak fitting was performed using the minimum number of chemically meaningful components required to reproduce each core level envelope. Additional peaks were introduced only when justified by the residuals or clear asymmetries in the spectra. A Shirley background was used in all cases, and peak shapes were described using a Gaussian-Lorentzian line shape GL(30) or an asymmetric Lorentzian line shape, LA(30) in CASAXPS, appropriate for lightly conductive oxide surfaces (84–86). Full fitting parameters and constraints for each experiment are reported in the Appendixes.

3.4 Fourier Transformed Infrared Reflection-Adsorption Spectroscopy (FT-IRRAS)

Infrared (IR) spectroscopy is widely used to identify chemical bonds and analyze vibrational structure. For surfaces, it is particularly useful because different functional groups and adsorption geometries give rise to characteristic vibrational “fingerprints”. Once a molecule is bound to a solid, its vibrational modes become sensitive to local coordination, charge transfer and hydrogen bonding. Monitoring how these bands evolve in the IR spectrum provides direct information on bonding, molecular orientation and surface reactivity (87).

The introduction of Fourier-transform infrared (FT-IR) spectroscopy in the 1960s was a key advance over earlier dispersive instruments (88). Using an interferometer instead of a monochromator allows all IR frequencies to be recorded simultaneously and separated mathematically by a Fourier transform.

For compact solids, conventional transmission IR is usually not practical because metals and many oxides are strongly absorbing or opaque in the mid-IR region. This motivated the development of reflection based techniques. Among these, Fourier-transform Infrared Reflection-Absorption spectroscopy (FT-IRRAS) has become a central method for studying adsorbates on well-defined surfaces under UHV conditions . In FT-IRRAS, spectra are recorded by ratioing the signal of the adsorbate covered surface to that of a clean reference surface, which enhances the weak vibrational features of the adsorbate and suppresses contributions from the substrate (89–92).

3.4.1 Theoretical Principles: the Anharmonic Oscillator

IR spectroscopy is based on the interaction between the oscillating electric field of the radiation and the vibrational motion of the atoms in a molecule. When the frequency of the field matches that of a vibrational mode that changes the molecular dipole moment, energy is absorbed and the system undergoes a transition between quantized vibrational levels (87). The resulting absorption bands are characteristic of particular bonds and local environments and therefore act as molecular fingerprints.

A diatomic bond can be treated as a harmonic oscillator, where the potential energy rises quadratically with displacement from equilibrium, like in Hooke's law. The potential energy $V(x)$ is expressed as

$$V(x) = \frac{1}{2} \cdot kx^2 \quad (\text{Eq. 14})$$

where k is the force constant related to bond strength. Solving the Schrödinger equation for this potential yield discrete energy levels

$$E_v = \left(v + \frac{1}{2} \right) \cdot h\nu_o \quad (\text{Eq. 15})$$

with h being Planck's constant, v the vibrational quantum number, and

$$\nu_o = \left(\frac{1}{2\pi} \right) \cdot \sqrt{\frac{k}{\mu}} \quad (\text{Eq.16})$$

the fundamental frequency, which depends on the reduced mass μ of the two atoms. In this harmonic approximation, only transitions following the selection rule $\Delta v = \pm 1$ are allowed, producing a single fundamental absorption band for each vibration.

Real chemical bonds are not perfectly harmonic. As the bond is stretched, the restoring force decreases and at sufficiently large separation the bond dissociates. A more realistic description is given by the Morse potential:

$$E_v = \left(v + \frac{1}{2}\right) \cdot h\nu_o - \left(v + \frac{1}{2}\right)^2 \cdot hx\nu_o \quad (\text{Eq. 17})$$

where x is the anharmonicity constant. Figure 3.4.1.1 compares the harmonic and Morse potentials: in the harmonic case the levels are equally spaced, whereas for the Morse potential the spacing decreases with increasing v . This anharmonicity shifts the fundamental band slightly to lower wavenumbers, allows overtones and combination bands ($\Delta v > 1$) and better reflects experimental spectra (87, 88).

The intensity of an infrared absorption band depends on how strongly the molecular dipole moment changes along a normal coordinate Q :

$$I \propto \left(\frac{\partial \mu}{\partial Q}\right)^2 \quad (\text{Eq. 18})$$

Only modes that induce a time dependent dipole moment are IR active. For example, symmetric stretches of homonuclear molecules such as O_2 or N_2 are inactive.

3.4.2 Reflection-Absorption Spectroscopy and Surface Selection Rules

When molecules adsorb on solid surfaces, the IR selection rules derived for isolated molecules are modified by the electromagnetic boundary conditions at the interface. The incident infrared beam

can be decomposed into electric field components that are parallel and perpendicular to the surface plane. How these components couple to the adsorbed dipoles depends strongly on the electronic properties of the substrate.

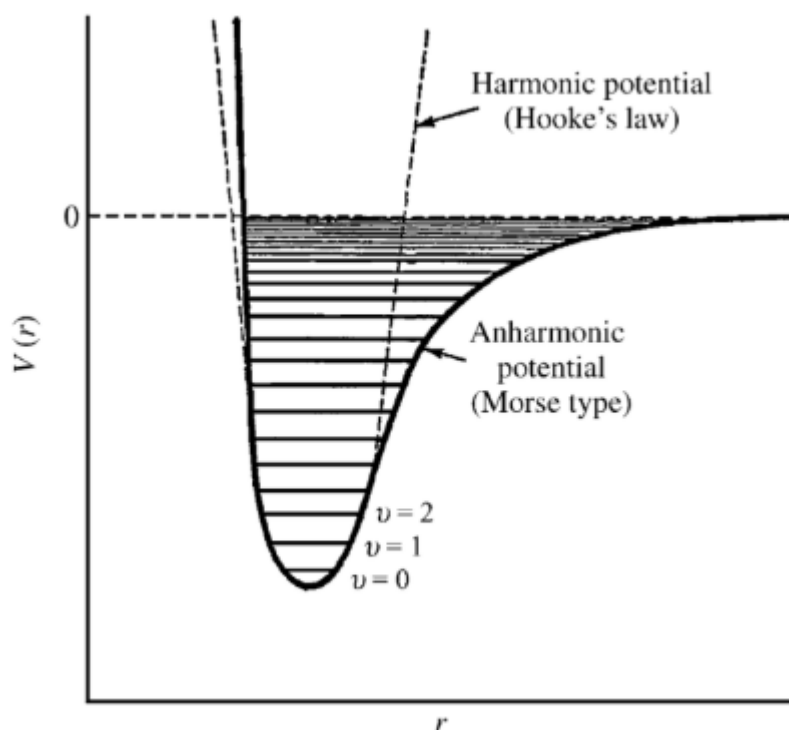


Figure 3.4.1.1. Schematic comparison between harmonic and anharmonic (Morse) potentials and their vibrational energy levels. Taken from (87).

On metallic surfaces, the high density of free electrons screens the incident field very efficiently. The electrons respond almost instantaneously to the oscillating field, generating an induced mirror charge that cancels the parallel component of the electric field at the surface. As a result, only the perpendicular component interacts with adsorbed dipoles. This leads to the surface selection rule: in reflection absorption geometry on metals, only vibrations that generate a dynamic dipole moment normal to the surface are IR active.

Figure 3.4.2.1 illustrate this situation. The incident p -polarized field (E_p) is decomposed into components parallel (E_{pt}) and perpendicular (E_{pn}) to the surface. The s -polarized component (E_s), which lies entirely parallel to the interface, is effectively cancelled by the conduction electrons and therefore does not contribute to absorption. In metals, the electromagnetic field is confined to the topmost atomic layer, and only E_{pn} interacts with adsorbed dipoles. For this reason, p -polarized light at grazing incidence (70 - 85°) is used almost exclusively in FT-IRRAS experiments on metallic single crystals such as Au(111) or Cu(110) (84, 85).

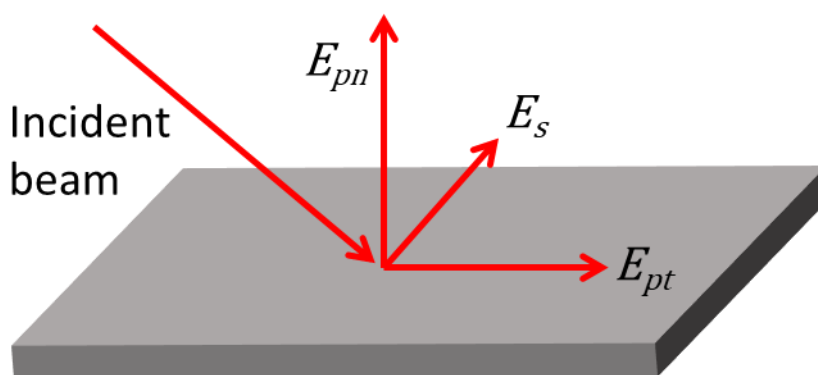


Figure 3.4.2.1 Schematic representation of the electric field components in IRRAS. The incident infrared beam is decomposed into three components: E_s and E_{pt} , which are polarized parallel to the surface, and E_{pn} , oriented perpendicular to the surface.

In contrast, dielectrics and semiconductors such as TiO_2 contain far fewer free carriers and therefore do not completely screen the incident field. The IR wave penetrates some distance into the solid and both parallel and perpendicular field components are present near the surface. Their relative amplitudes depend on the complex refractive index ($n + ik$) and the angle of incidence, as described by the Fresnel reflection coefficients. For p polarization, the reflected field amplitude can be written in terms of the refractive indices of the surrounding medium and the substrate and the incidence/refraction angles:

$$r_p = \frac{n_2 \cdot \cos \theta_1 - n_1 \cdot \cos \theta_2}{n_2 \cdot \cos \theta_1 + n_1 \cdot \cos \theta_2} \quad (\text{Eq. 19})$$

here n_1 and n_2 are the refractive indices of the surrounding medium and the substrate, respectively, and θ_1 and θ_2 are the incidence and refraction angles.

The penetration depth of the infrared field in an absorbing solid is given by

$$\delta = \frac{\lambda}{4 \cdot \pi \cdot k} \quad (\text{Eq. 20})$$

where λ is the wavelength and k the extinction coefficient (93). Experimental studies on $\text{TiO}_2(110)$ have clearly demonstrated this difference. For instance, the symmetric and asymmetric O-C-O stretching vibrations of bidentate formate species show polarization dependent intensity variations, reflecting the coexistence of both field components near the surface (45, 47, 94). These effects make it possible to determine the orientation of molecular groups relative to the substrate and to distinguish between different adsorption geometries (95).

3.4.3 Michelson Interferometer

The key component that distinguishes Fourier-transform infrared spectroscopy from earlier dispersive techniques is the Michelson interferometer. Instead of using a monochromator to select one wavelength at a time, the interferometer records an interferogram that contains contributions from all wavelengths simultaneously. A Fourier transform then recovers the conventional spectrum (88, 96).

The interferometer is made of a broadband IR source, a beam splitter, and two mirrors (one fixed, one movable) at right angles. The splitter divides the beam into two paths that recombine after reflection. As the movable mirror translates, the optical path difference changes and the beams interfere constructively or destructively depending on phase. The detector records intensity versus mirror position, producing an interferogram. This arrangement is sketched in Figure 3.4.3.1a.

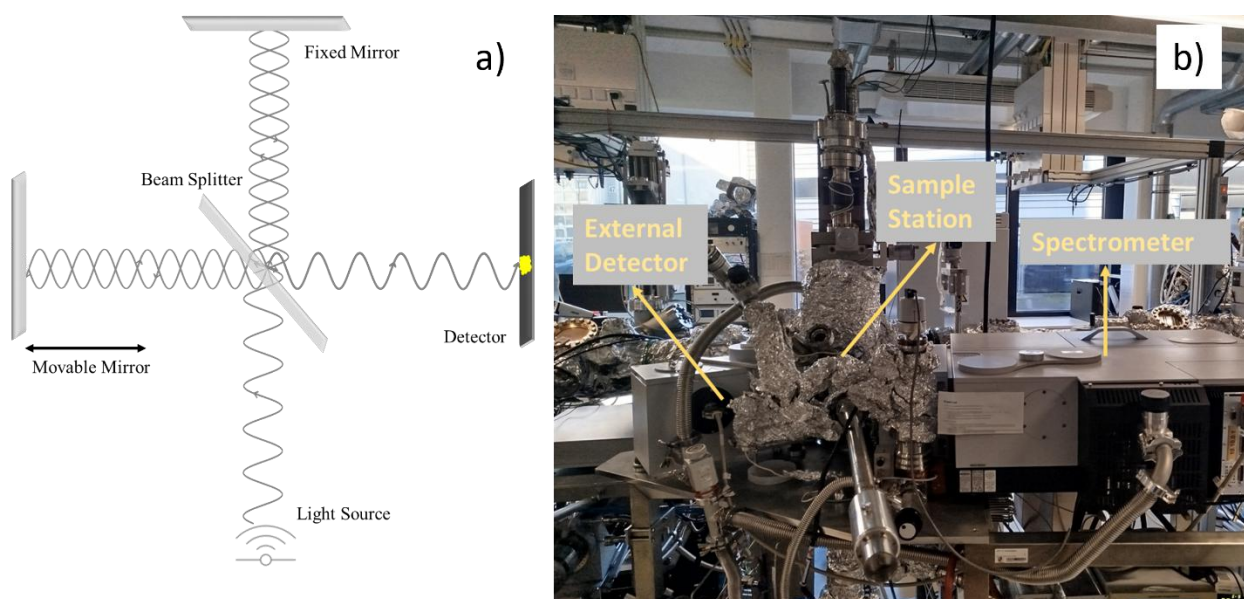


Figure 3.4.3.1 a) Schematic representation of a Michelson interferometer used in FT-IR spectroscopy. b) Picture of DESY Nanolab laboratory setup (67).

3.4.4 Equipment and Experimental Parameters

FT-IRRAS experiments were performed using a FT-IR Vacuum-spectrometer from Brüker, Model VERTAX 80v with an external MCT detector for the measurements in Reflection and an Internal DTG detector for the measurements in transmission. The UHV chamber reached a base pressure of low 10^{-10} mbar. Each IR spectrum was taken in reflection mode with 512 scans at a resolution of 2 cm^{-1} during 5 minutes. Setup is shown Figure 3.4.3.1b.

3.5 Scanning Tunneling Microscopy

The scanning tunnelling microscope (STM) was developed by Gerd Binnig and Heinrich Rohrer at IBM Zurich in 1981 and showed that individual atoms on solid surfaces could be imaged in real space under well-controlled conditions (97, 98). Unlike optical or electron microscopes, STM does not use lenses or focused beams. It takes advantage of quantum mechanical tunnelling of electrons between a sharp metallic tip and a conductive surface.

3.5.1 Theoretical Background and Principles

In classical physics, an electron with energy E lower than a potential barrier of height U_0 cannot cross it. Quantum mechanics, however, predicts a finite probability that the electron wavefunction penetrates and passes through the barrier, even when $E < U_0$ and this is what makes STM measurements extremely sensitive to small changes in tip-sample separation.

When a bias voltage U_0 is applied between a metallic tip and a conductive sample, electrons tunnel through the vacuum barrier separating them. Within the Bardeen transfer Hamiltonian formalism and Fermi's golden rule, the total tunnelling current is obtained by summing all transitions between occupied states of one electrode and empty states of the other:

$$I = \left(\frac{4\pi e}{\hbar} \right) \int_{E_F - eU_0}^{E_F} |M_{ts(\varepsilon)}|^2 \rho_t(\varepsilon + eU_0) \rho_s(\varepsilon) d\varepsilon \quad (\text{Eq. 21})$$

where e is the elementary charge, $\hbar$ the reduced Planck constant, M_{ts} the tunnelling matrix element describing the overlap of the tip and sample wavefunctions, and ρ_t and ρ_s their respective local densities of electronic states (LDOS) (99–101).

A more intuitive expression was derived by Tersoff and Hamann. Approximating the tip by an s-type orbital at a distance d above the surface and assuming a small bias and weak coupling, the current becomes proportional to (100):

$$I \propto U_b \rho_t(E_F) \rho_s(E_F, r_0) \exp \left[- \left(\frac{2}{\hbar} \right) \sqrt{2 m \Phi_{eff}} \cdot d \right] \quad (Eq. 22)$$

Here m is the electron mass, d the tip-sample distance, and Φ_{eff} the effective barrier height, typically close to the average work function of the tip and surface. The exponential factor originates from the decay of the electron wavefunction within the vacuum gap, where the amplitude decreases with increasing distance according to

$$\psi(z) \sim e^{(-\kappa d)} \text{ with } \kappa = \frac{\sqrt{(2 m (\Phi - E))}}{\hbar} \quad (Eq. 23)$$

This expression shows how the probability density of the electron decreases as it travels from the surface towards the tip through the vacuum barrier. Because the tunnelling current is proportional to the square of the wavefunction amplitude, it acquires an exponential dependence of the form.

$$I \propto e^{-2\kappa d} \quad (Eq. 24)$$

For a typical barrier height of 4-5 eV, κ is about $1 \text{ \AA}^{-1}$, which means that increasing the tip to sample distance by just one ångströms reduces the tunnelling current by roughly an order of magnitude. This extreme sensitivity is what enables the STM to resolve sub ångströms variations in height but also requires exceptional mechanical stability and vibration isolation.

The full expression in Eq. 22 therefore combines both the electronic structure of the material, contained in the LDOS terms $\rho_t(E_F)$ and $\rho_s(E_F, r_0)$ and the geometric factor arising from the

exponential tunnelling probability. STM images are thus not simple height maps. The contrast reflects how electronic states extend into the vacuum: areas with a higher LDOS appear brighter at constant height because they sustain a larger tunnelling current. In this way, STM provides information that is both structural and electronic at the same time. This interpretation has been extensively validated on TiO₂ surfaces, where atomically resolved STM images directly reflect the LDOS associated with Ti_{5c} rows, oxygen vacancies and subsurface defects (102–105).

More detailed derivations of these formalisms, including Bardeen’s transfer Hamiltonian, Fermi’s golden rule and the Tersoff-Hamann approximation, can be found in standard STM textbooks and review articles (99–101).

3.5.2 Equipment and Experimental Parameters

All STM experiments were performed in a UHV AFM XA system from Omicron with a base pressure of $5 \cdot 10^{-11}$ mbar. The system is mechanically decoupled from the main building sitting on a separated baseplate, and air damping legs are used for further vibration control. Imaging is performed using a constant tunnelling current mode and a tungsten tip. Dataset specific imaging conditions are provided in the Appendix 1-3. The system was operated by the MATRIX software, whereas Gwyddion was used for image processing (106).

4: Unravelling the Role of the Multi-Functional Groups in the Adsorption of L-Cysteine on Rutile TiO₂(110)

Titanium dioxide (TiO₂) remains one of the most widely studied metal oxides due to its ability to enable light-driven processes such as water splitting (107), the degradation of organic pollutants (108), and the inactivation of microorganisms (109). These characteristics, together with its abundance, non-toxicity, and chemical stability, have positioned TiO₂ at the center of diverse technological applications, including water purification (110), antiviral self-cleaning coatings (111, 112), and air purification systems (113).

Recent studies have shown that TiO₂ can also deactivate viruses by degrading their outermost protein layers, including the spike proteins of SARS-CoV-2 (1, 2). Since the destruction of these protein shells directly compromises viral integrity, understanding how biological macromolecules interact with TiO₂ surfaces has become essential for designing next-generation disinfection materials (114, 115).

A major difficulty in this field is the size and structural heterogeneity of proteins. Their large number of molecules and diversity of functional groups make it hard to isolate the elementary chemical steps that govern adsorption and degradation at oxide surfaces. A common strategy is therefore to reduce the system complexity. Amino acids are the structural building blocks of proteins, and their adsorption behaviour is expected to influence how larger biomolecules anchor, reorganize or degrade at inorganic interfaces. Rutile TiO₂(110), in particular, is a convenient model surface because it is the most thermodynamically stable termination of rutile (22, 116) and has been extensively characterized in adsorption studies involving water (117, 118), carboxylic acids (119–123) and small amino acids (38, 42, 124, 125).

Among amino acids, L-cysteine is a particularly useful probe because of its multifunctional character. In addition to the universal amine and carboxylate groups, cysteine carries a thiol group that can undergo oxidation, disulfide formation and metal coordination. Previous investigations have shown that the amine carboxylate backbone is almost always involved in adsorption (126). The role of the thiol group, however, is less clear and has been the subject of conflicting reports. Some theoretical studies suggest that cysteine binds predominantly through its carboxylate group in bidentate (O,O) configurations, sometimes stabilized by proton transfer involving the thiol (55, 57). Experimentally, XPS studies on cysteine have reported bidentate bridging geometries accompanied by interactions between sulphur atoms and Ti ions at oxygen vacancies, possibly involving C-S bond cleavage (53, 54). These conclusions differ from most theoretical predictions, which do not anticipate C-S bond rupture. In addition, reactive force field simulations have suggested that thiol chemistry at the surface may play a role (127, 128). Taken together, these contrasting results highlight several open questions regarding (i) the preferred adsorption state of cysteine (molecular, deprotonated or zwitterionic), (ii) the exact binding geometries, whether purely carboxylate-bridging or involving the amine and thiol groups, (iii) the preferred adsorption sites on the TiO₂(110) surface and (iv) the possibility of intermolecular processes such as dimerization (129).

The aim of this chapter is to obtain a detailed mechanistic picture of L-cysteine adsorption on rutile TiO₂(110) under controlled ultrahigh vacuum (UHV) conditions. In particular, we seek to identify the stable adsorption configurations, determine how the different functional groups contribute to binding, and assess the influence of intermolecular interactions.

To achieve this, a multi technique strategy combining X-ray photoelectron spectroscopy, Fourier-transform infrared reflection absorption spectroscopy, scanning tunnelling microscopy, and density functional theory calculations was employed. XPS allowed us to identify the protonation state of cysteine and distinguish between different binding geometries by analyzing core-level shifts in the C 1s, N 1s, O 1s, and S 2p regions. FT-IRRAS provided complementary evidence through vibrational fingerprints characteristic of carboxylate binding geometries, $\text{NH}_2/\text{NH}_3^+$ species. STM imaging revealed the adsorption morphology, distinguishing isolated molecules from paired features consistent with cysteine dimers. Finally, DFT simulations provided adsorption energies, equilibrium geometries, and detailed information of the electronic structure and noncovalent interactions stabilizing the observed configurations.

At room temperature, cysteine adsorption on rutile (110) follows a common structural pattern. In all observed cases, the molecule binds in a bridging bidentate fashion to two adjacent Ti_{5c} atoms within the same Ti row, oriented along the $[\bar{1}\bar{1}0]$ direction. STM images provide direct evidence for this adsorption geometry, as individual molecular features are consistently aligned along the Ti_{5c} rows.

Within this general adsorption scheme, several binding configurations are identified depending on which functional groups participate in coordination. The first configuration corresponds to the classical bidentate (O,O) geometry, in which both oxygen atoms of the deprotonated carboxylate group bind to two Ti atoms. This adsorption mode has been widely reported for carboxylate containing molecules on rutile (110) and serves as a reference configuration for amino acid adsorption on this surface.

In addition to this configuration, we identify (O,N) geometry, where one carboxylate oxygen and the nitrogen atom of the amino group coordinate to adjacent Ti_{5c} atoms. Density functional theory calculations show that this (O,N) configuration is energetically more stable than the purely carboxylate based (O,O) configuration on rutile, in agreement with the relative intensities observed in the spectroscopic data.

Evidence for a third adsorption configuration arises from the XPS measurements. In the S 2p region, a sulphur component is detected at 161.7 eV characteristic of sulphur bonded to a metal center, indicating the presence of a configuration in which sulphur directly interacts with surface titanium atoms. The observation of this S-Ti contribution implies that at least part of the cysteine population adsorbs in a mixed (O,S) geometry. This experimental finding motivated further DFT calculations, which demonstrate that the (O,S) configuration is nearly as stable as the (O,O) configuration, confirming that direct sulphur coordination is energetically viable on the rutile surface.

FT-IRRAS and XPS measurements provide complementary information on the protonation state of the adsorbed molecules. Vibrational spectra reveal contributions associated with both neutral NH_2 and protonated NH_3^+ groups, while the N 1s core level spectra show distinct components corresponding to these two chemical states. These observations indicate that a fraction of the adsorbed cysteine molecules adopts a zwitterionic configuration under the present experimental conditions. Density functional theory calculations show that this zwitterionic state becomes energetically stable in the presence of a small number of water molecules, which can provide additional hydrogen bonding and electrostatic stabilization. This result suggests that proton transfer can involve not only interactions between the molecule and the surface, as previously

discussed in the literature, but also intramolecular proton transfer from the carboxylate group to the amino group when residual water is present.

STM images also reveal molecular features with an apparent size approximately twice that of individual cysteine molecules, consistent with the presence of adsorbed dimers. Motivated by this observation, density functional theory calculations were performed to determine the nature of these dimeric species and to distinguish between hydrogen bonded dimers and dimers linked by disulfide bridges. The calculations show that dimer configurations involving S-S bond formation are energetically more stable than hydrogen bonded. This result supports the assignment of the observed STM features to cysteine dimers connected through disulfide bonds.

Disulfide bridges are a key structural element in proteins, providing mechanical and conformational stability to their three dimensional structures. Their formation and cleavage directly affect protein folding and denaturation. The formation of disulfide linked cysteine dimers on TiO_2 , thus, provides a molecular level example of how oxide surfaces can affect sulphur based biomolecular structures.

Within the broader context of this thesis, this study provides the starting point for understanding amino acid adsorption on TiO_2 surfaces. The atomic-level picture established here forms the basis for the subsequent chapters, which address asparagine adsorption, photocatalytic oxidation of cysteine on anatase TiO_2 and comparative trends across different TiO_2 polymorphs.

Unraveling the Role of the Multifunctional Groups in the Adsorption of L-Cysteine on Rutile TiO₂(110)

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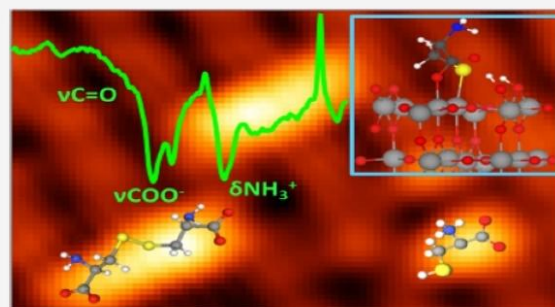
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ABSTRACT: Understanding the interaction between biomolecules and oxide surfaces is essential for advancing technologies in photocatalysis, virus inactivation, and self-cleaning materials. This study investigates the adsorption behavior of L-cysteine on the rutile TiO₂(110) surface using a combined experimental and theoretical approach. By employing X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared reflection absorption spectroscopy (FT-IRRAS), scanning tunneling microscopy (STM), and density functional theory (DFT) calculations, we elucidate the molecular configurations and bonding mechanisms involved in the interaction of cysteine with the TiO₂ surface. The results reveal three distinct adsorption geometries: two bidentate bridging modes involving the carboxylate group and amino group and a configuration involving the interaction of the thiolate group with titanium atoms. Additionally, cysteine molecules form dimers stabilized by disulfide bonds even at low coverage while maintaining a zwitterionic state. Our study highlights, for the first time, the key role of the thiol group in cysteine adsorption on TiO₂, both for surface direct binding and dimer formation. These findings provide new insights into the fundamental principles of biomolecule–semiconductor interactions with important implications for surface-functionalized materials in catalysis and sensing.



INTRODUCTION

Titanium dioxide (TiO₂) is renowned for its remarkable photocatalytic properties, enabling critical chemical processes such as water splitting,¹ degrading organic pollutants,² and microorganisms.³ These properties, along with the fact that TiO₂ is a nontoxic compound and is widely available, have made it central to various industrial applications, including water treatment,⁴ disinfection technologies, such as antiviral, self-cleaning surfaces,^{5,6} and air purification systems.⁷

TiO₂ has demonstrated excellent efficacy in inactivating viruses. Recent studies have highlighted its ability to neutralize the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) by targeting and degrading the virus's outermost layer (spike proteins).^{8,9} Previous investigations have demonstrated that degradation of the spike proteins can lead to the ultimate inactivation of the virus, increasing the interest in understanding the interaction between the spike proteins at the interface with the TiO₂ surfaces.^{10,11}

The rutile (110) surface is the thermodynamically most stable termination of rutile and, moreover, is one of the most extensively studied oxide surfaces.^{12,13} Numerous studies have explored the adsorption behavior of various small and large molecules on the TiO₂(110) surface, including water,¹⁴

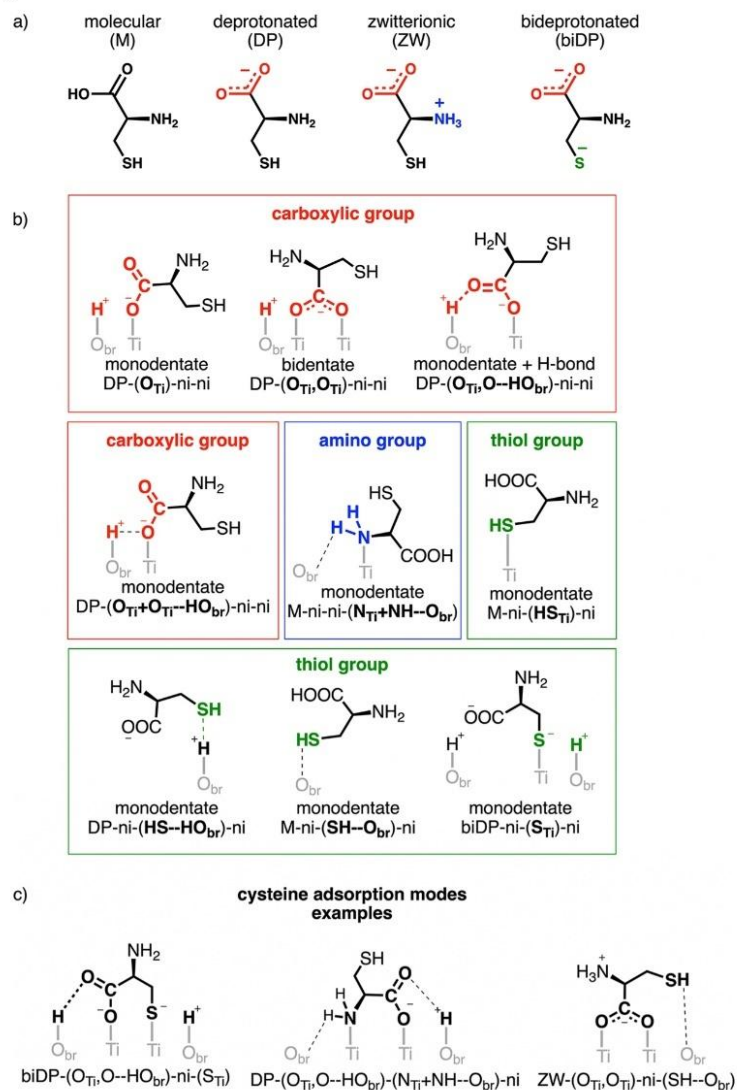
carboxylic acids,^{15–17} and lipids among others.^{18–27} Understanding its interaction with amino acids, the protein building blocks, is a crucial step to fully understand the interaction behavior of the virus and other pathogens with the surface of oxide photocatalysts.

Several experimental and computational studies have investigated the adsorption of amino acids on rutile TiO₂(110).^{28,29} While previous findings suggest a preferred adsorption mode via dissociation of the carboxylic group, variations in behavior arise depending on the type of the amino acid and the presence of water at the surface. For instance, Yazdanyar et al. found that the backbone of amino acids, comprising the amine and carboxyl groups, universally participates in adsorption across all types of amino acids while only the polar or charged side-chains can promote the adsorption process.³⁰

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Scheme 1. Structures of (a) Investigated Protonation Forms of Cysteine, (b) Possible Adsorption Models of the Different Carboxylic (Red), Amino (Blue), and Thiol (Green) Functional Groups of Cysteine on the TiO₂ Surface, and (c) Examples of Relevant Cysteine Adsorption Modes



Among amino acids, L-cysteine (cys) stands out for its unique characteristics. As one of the smallest amino acids, it exhibits significant chemical complexity due to the presence of three distinct functional groups: carbonyl, amino, and thiol. Notably, L-cysteine is the only amino acid containing a thiol group. Additionally, the tendency of cysteine molecules to form disulfide bonds is well-known for strengthening the structural integrity and three-dimensional stability of proteins.^{31,32} Also, cysteine is one of the most abundant amino acids in the spike protein of SARS-CoV-2, highlighting the importance of understanding the adsorption behavior of this molecule with photoactive catalysts.³³

Despite experimental^{34,35} and theoretical^{36,37} investigations, the precise nature of the cysteine-TiO₂ interactions remains unresolved due to inconsistencies between observed and predicted results. Pantaleone et al. proposed, based on DFT conclusions, that cysteine preferentially adsorbs on the

TiO₂(110) surface in a bidentate bridging configuration (O,O), where the carboxylate group interacts with two 5-fold-coordinated Ti atoms (Ti_{5c}).³⁶ The authors suggested that both deprotonated and zwitterionic cysteine configurations are energetically similar, with the sulfur group remaining unbound to the surface. Muir and Idriss computed two stable binding modes: the same bridging bidentate COO-Ti (O,O) and also a bridging through Ti-OOC-H₂N-Ti (O)-(N), through DFT calculations.³⁷ In some of the modes in which cysteine is binding through (O,O), the authors observed a stabilization interaction through the thiol group via proton transfer with a surface oxygen. The involvement of the thiol group in cysteine adsorption was also suggested by classical nonreactive and reactive force field calculations.^{38,39} An experimental study using XPS³⁴ reported the cysteine adsorption through the carboxylate group in a bridging bidentate (O,O) configuration with sulfur atoms interacting with titanium ions at oxygen

complete agreement with a previous study by Muir and Idriss as it will be discussed below.³⁷

Our calculations indicate that the carboxylic group of cysteine dissociates upon adsorption (deprotonated cysteine, DP), transferring a proton to a nearby surface bridging O atom. This process involves one or two under-coordinated surface Ti_{5c} atoms, which form coordinative bonds with one or two carboxylate O atoms (monodentate or bidentate), as shown in Scheme 1. In all cases that we investigated, the deprotonated cysteine molecules establish at least two or more different interactions with the surface atoms. The most stable geometries, those having the lowest (i.e., most negative) adsorption energies, are illustrated in Figures 1 and S3. In the first configuration (Figure 1a), two interactions are the bidentate binding of the two carboxylate O with two neighboring Ti_{5c} , whereas the third is an electrostatic attraction between the S atom of the thiol group with the dissociated proton bound to a surface bridging O atom ($\text{DP}-(\text{O}_{\text{Ti}}\text{O}_{\text{Ti}})\text{-ni}-(\text{HS}-\text{HO}_{\text{br}})$). In the second configuration (Figure 1b), one interaction is the coordinative bond of one carboxylate group O with a surface Ti_{5c} atom, the second interaction is the coordinative bond of the N atom of the amino group with another surface Ti_{5c} atom, and then there are two H-bonds established between the bridging OH group with the unbound carboxylate O atom and between the NH group of amino with a surface bridging O atom ($\text{DP}-(\text{O}_{\text{Ti}}\text{O}-\text{HO}_{\text{br}})\text{-(N}_{\text{Ti}}+\text{NH}-\text{O}_{\text{br}})\text{-ni}$). We also explored the involvement of the thiol group in the cysteine surface adsorption, as suggested by Monti et al.,^{38,39} and reported the most stable structures. In the third configuration (Figure 1c), one interaction is the coordinative bond of one carboxylate O with a surface Ti_{5c} atom, and the second interaction is the coordinative bond of the S atom of the dissociated thiol group with another surface Ti_{5c} atom ($\text{biDP}-(\text{O}_{\text{Ti}}\text{O}-\text{HO}_{\text{br}})\text{-ni}-(\text{S}_{\text{Ti}})$). Additionally, in the $\text{biDP}-(\text{O}_{\text{Ti}}\text{O}-\text{HO}_{\text{br}})\text{-ni}-(\text{S}_{\text{Ti}})$ structure, one H-bond is established between one bridging surface OH group with the unbound carboxylate O atom, and an electrostatic interaction is formed between the other bridging surface OH group and the S atom. Notably, the $\text{biDP}-(\text{O}_{\text{Ti}}\text{O}-\text{HO}_{\text{br}})\text{-(ni)}-(\text{S}_{\text{Ti}})$ is a highly stable new adsorption configuration that was never reported in previous studies.^{36–39} In the fourth configuration (Figure 1d), one interaction is the coordinative bond of one carboxylate O with a surface Ti_{5c} atom, whereas the second is between the S of the undissociated thiol group and another surface Ti_{5c} atom, although the Ti-SH distance is extremely long (4.53 Å) ($\text{DP}-(\text{O}_{\text{Ti}})\text{-ni}-(\text{HS}_{\text{Ti}})$).

The trend in the adsorption energy for these four configurations does not change whether the Hubbard U correction is used (Table S1). Therefore, we can conclude that adsorption modes involving direct interaction of the deprotonated thiol S atoms with surface Ti atoms are comparable with those involving carboxylate O atoms. The preferred configuration, however, uses both one carboxylate atom and the amino N atom to coordinate with two surface Ti_{5c} . We have also investigated the role played at higher coverages by introducing two cysteine molecules into the same supercell slab model used before (Figure S4). We observed that the structures exhibit the same energy trend as when the molecules were individual adsorbates, but with a slightly enhanced stabilization due to an additional H-bond formed between the two structures (Table S3).

From the experimental side, XPS were obtained on a clean rutile (110) surface before and after cysteine adsorption. The

surface preparation, characterization methods, and coverage calculation can be consulted in the Supporting Information. Experiments were performed at the DESY Nanolab.⁴⁴ The clean sample showed no contamination from carbon, hydroxyl, or water in XPS and displayed a LEED pattern representative of a stoichiometric (1×1) rutile (110) surface (Figure S1). Cysteine was dosed onto the surface until saturation corresponding to approximately one monolayer was achieved. After cysteine adsorption, the deconvoluted C 1s core-level spectrum, depicted in Figure 2a, reveals three distinct peaks with three chemically inequivalent carbon atoms in a ratio of 1:1:1. The peak with the higher binding energy corresponds to the carboxylic carbon at 289.0 eV. The second peak, at slightly lower binding energies at 286.1 eV, corresponds to the α -carbon of the amino acid. The third peak at 285.2 eV is attributed to the carbon bonded to sulfur. In order to provide an additional tool for comparing the optimized adsorption configurations with the experimental measurements, we performed a spectroscopic characterization through simulated photoemission spectra. However, we cannot calculate absolute values for the binding energies through our approach (see the Supporting Information for further details), but we can only obtain relative differences, i.e., core-level shifts (CLSs). From the calculated CLSs, which are collected in Table S4, it is possible to reveal three spectroscopic features at the C K-edge, separated by 0.6 eV (C–S to C–N) and 1.9 eV (C–N to C–O). Experimentally, these energy differences are 0.9 and 2.9 eV, respectively. Although the calculated energy separations are underestimated compared to experimental results, such discrepancies have been reported previously for other molecules adsorbed on rutile (110) surfaces.⁴⁵ Due to the small energy differences among the computed CLS values for the different geometries, it remains challenging to conclusively assign a specific adsorption geometry only based on the C 1s spectrum. This is a consequence of the presence of a carboxylate group interacting with the surface in all of the adsorption models. In the case of the (O)-(S) geometry, the additional interaction of the deprotonated thiol group with a Ti atom reduces the binding energy of the α -carbon and the C in the thiol side-chain. This observation aligns with previous findings of the adsorption of cysteine on the rutile (110) surface.^{34,35,46} However, contrary to Ataman et al.,^{34,35} we do not observe any degradation or breaking of the cysteine molecule. We believe that the bond breaking observed in their work may be attributed to radiation damage coming from the synchrotron source or contaminants.

Figure 2b shows the deconvoluted O 1s spectrum for the clean rutile (110) surface. The main peak at 530.4 eV corresponds to lattice oxygen in TiO_2 , while the secondary component at 531.2 eV has been previously linked to either bridging oxygens or hydroxyl species. However, its origin remains debated and may reflect an intrinsic feature of the TiO_2 lattice or a slight peak asymmetry.^{47,48} Upon cysteine deposition, a new oxygen peak emerged at a binding energy of 532.1 eV. This peak is characteristic of oxygen atoms in carboxylic compounds, as previously observed during glutamic acid adsorption.⁴⁹ Notably, the cysteine molecule contains two distinct oxygen atoms ($\text{CO}^1\text{O}^2\text{H}$), which, if protonated, would typically result in two separate peaks with a binding energy difference of approximately 2 eV, according to our gas-phase calculations. The proton-bonded oxygen would be expected to display a higher binding energy, exceeding 533.5 eV.^{50,51} The

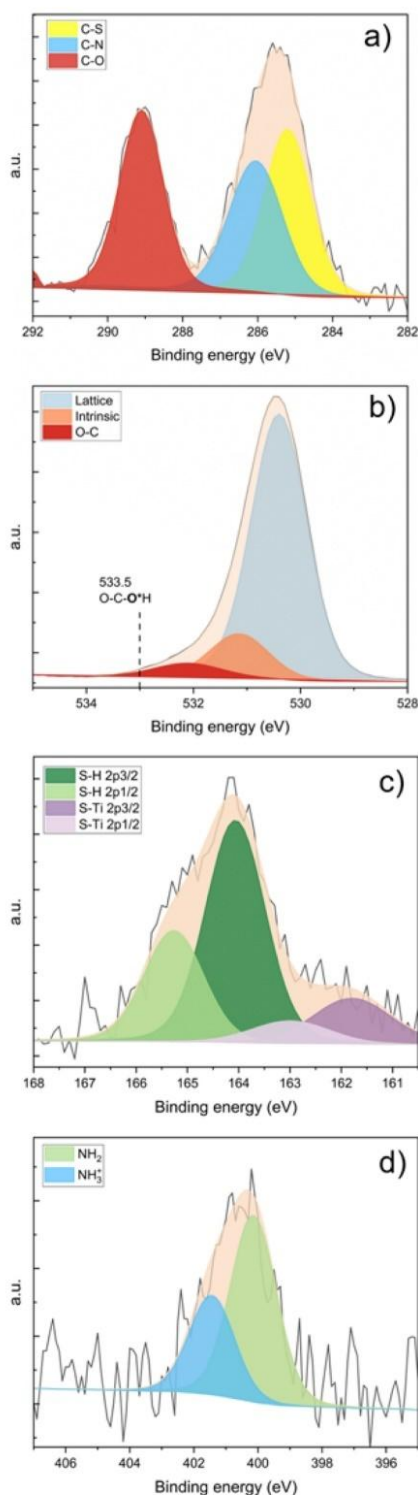


Figure 2. Experimental (black lines) and deconvoluted XP spectra (colored areas) of the (a) C 1s, (b) O 1s, (c) S 2p, and (d) N 1s core levels.

absence of this peak implies the loss of an acidic proton upon adsorption on the TiO₂ surface.

Theoretical calculations provide further insight into the observed XP spectral features. For bidentate (O)-(N) configurations, the two oxygen atoms in cysteine are chemically inequivalent with calculated CLSs that differ by approximately 0.1 eV (see Table S4 for a comparison of the calculated values for the different geometries). Such differences are notably smaller than those calculated for adsorption structures obtained with more approximate ReaxFF simulations.^{38,39} The differences are so small that due to limitations with the achievable experimental resolution, resolving this component is difficult, particularly given the relatively low intensity of this peak compared to the lattice oxygen peak.⁵² For comparison, studies on Fe₃O₄ have shown that carboxylate species yield a single peak at 531.6 eV.⁵³ Thus, the O 1s spectrum alone cannot definitively distinguish between the bridging (O,O) and (O)-(N) configurations.

Figure 2c illustrates the deconvoluted XP spectra of the S 2p core level, revealing the presence of two distinct sulfur species with the characteristic doublets separated by 2.4 eV. The lower binding energy 2p_{3/2} peak at 161.7 eV is attributed to sulfur bound to the titanium, Ti_{5c}, like in structure DP (O)-(S) (Figure 1c), while the higher binding energy 2p_{3/2} peak at 164.1 eV corresponds to the thiol (S-H) group in the cysteine molecule. The different CLSs for S-H in both DP (O)-(N) and DP (O)-(O) are not so big as to resolve with precision these two structures. To adequately fit the spectra, a spin-orbit splitting of 1.2 eV was applied to the S 2p_{1/2} and S 2p_{3/2} peaks, with an area ratio of 1:2. The area ratio between the two sulfur species is 1 (S-H) to 0.3 (S-Ti). Ataman et al. assigned the lower binding energy peak to a sulfur bounded to a titanium atom in an oxygen vacancy.^{34,35} However, our Ti 2p spectra before and after cysteine deposition show no significant change in the Ti³⁺ signal (see Figure S2), maintaining a Ti⁴⁺/Ti³⁺ ratio of approximately 1:0.05. This low concentration of oxygen vacancies suggests that most cysteine molecules do not interact with defect sites. Instead, the presence of both S-H and S-Ti species likely reflects the coexistence of multiple adsorption mechanisms on the surface at this coverage. Our theoretical simulations verify this hypothesis, as we find two main sulfur features among the different calculated CLSs (see Table S4), corresponding to S-Ti or S-H bonding configurations. These two features are separated by 1.9 eV, which agrees with previous ReaxFF-driven calculations^{38,39} and compares well with the experimental observations (2.4 eV between species). To further clarify the binding mode and geometry of cysteine on TiO₂, FT-IRRAS was employed (see Figure 3). If the bidentate binding mode (O,O) is the predominant mechanism of the dissociative adsorption of cysteine on rutile (110), we would expect to observe two distinct bands corresponding to the asymmetric (ν_{asym}) and symmetric (ν_{sym}) stretching vibrations of OCO. Studies performed on other acids, such as formic acid or L-alanine, show that we can expect the $\nu_{\text{asym}}(\text{OCO})$ and $\nu_{\text{sym}}(\text{OCO})$ bands around 1550 and 1370 cm⁻¹ on oxide surfaces, respectively.^{54,55}

At low coverage, the presence of a carbonyl (C=O) stretching vibration is observed at around 1670 cm⁻¹. This indicates monodentate adsorption, likely involving either (O)-(N) or (O)-(S). Nara et al.⁶⁰ calculated similar frequencies for C=O stretching configurations where the carboxylic group interacts with a single titanium atom. At higher coverages, additional bands are observed at 1585 and 1363 cm⁻¹, assigned to the $\nu_{\text{asym}}(\text{OCO})$ and $\nu_{\text{sym}}(\text{OCO})$, respectively. Pászti and

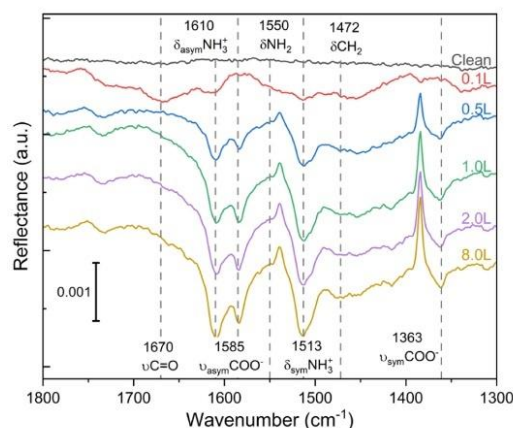


Figure 3. FT-IRRAS spectra for different coverages of cysteine on rutile $\text{TiO}_2(110)$ at room temperature.

Guczi⁶¹ describe band positions and splitting for different OCO configurations of adsorbed amino acids on TiO_2 . In monodentate configurations, $\nu_{\text{asym}}(\text{O}=\text{C}-\text{O}-\text{Ti})$ is always above 1600 cm^{-1} , similar to carbonyl stretching.

In the case of aspartic and glutamic acids, it is typically around $1660\text{--}1680\text{ cm}^{-1}$. For bridging bidentate adsorption (O,O), the separation between $\nu_{\text{asym}}(\text{OCO})$ and $\nu_{\text{asym}}(\text{OCO})$ is around 200 cm^{-1} comparable to what we observe. Similar splittings of 200 cm^{-1} were reported previously for formate adsorption on rutile (110) and on other oxide surfaces.^{58,59,62} For comparison, the dissociative adsorption of formic acid on TiO_2 showed bands at 1555 and 1370 cm^{-1} and on zinc oxide at 1573 and 1374 cm^{-1} .^{59,62} The sharp, upward-pointing band at 1385 cm^{-1} is a reproducible interferometer absorption artifact unrelated to cysteine adsorption. The corresponding background trace is provided in Figure S10.

To support the assignment of the experimental peaks, we computed the vibrational normal modes and corresponding frequencies for the three most stable deprotonated configurations (Figure 1a–c). The theoretical frequencies were then compared to the experimental data. The results, summarized in Table 1, show an overall good agreement between theory and experiment. To achieve high accuracy in the vibrational analysis, hybrid DFT methods are considered superior to standard DFT approaches such as GGA-PBE, which was used in the present study (PBE-D3+U).⁶³

We also assessed the thermodynamic stability at room temperature of the most stable adsorption modes (Figure 1a–c)

by computing the Gibbs free energies of adsorption (ΔG). From these values, we estimated the corresponding desorption temperatures using the Redhead approximation,⁶⁴ assuming a pre-exponential factor of 10^{13} Hz and a heating rate of 1 K/s , as reported in Table S6. All ΔG values are sufficiently negative to ensure stable adsorption at RT and up to $T < 146\text{ }^\circ\text{C}$.

These results, in combination with XPS data and the theoretical models, clearly indicate that cysteine adsorbs on the TiO_2 surface in three distinct configurations: bidentate (O,O), bidentate (O)-(N), and bidentate (O)-(S) (Figure 1a–c).

Zwitterionic Cysteine. Figure 2d presents the deconvoluted XP spectrum of the N 1s core level, revealing two distinct nitrogen peaks. The lower binding energy peak, colored green, at 400.1 eV is assigned to the amino ($-\text{NH}_2$) group. The calculated CLSs for this nonprotonated group are similar for the various structural models and match those predicted for the NH_2 group of the molecule in the gas phase (see Table S4). Similar differences were reported in the case of adsorption configurations obtained through ReaxFF calculations.³⁸ Slightly less negative CLSs are observed in configurations where the amino group interacts more strongly with the surface, with either a Ti_{sc} or an O_{br} atom. This behavior is similar to what was previously calculated for cysteine adsorbed on the anatase $\text{TiO}_2(101)$ surface through the formation of a hydrogen bond.⁶⁵ However, due to the limited spectral resolution and the broadness of the peaks, combined with the small energy separation between the different NH_2 species, it is not possible to distinguish between both of them experimentally. Therefore, both strongly and weakly interacting NH_2 species are grouped under a single NH_2 assignment.

The higher binding energy peak in blue is assigned to ($-\text{NH}_3^+$). The observed peak splitting of 1.5 eV is consistent with previous experimental results; a splitting of 1.5 eV has been reported before for glutamic acid on rutile (110) and falls within the $1.5\text{--}2.5\text{ eV}$ range commonly reported for amino acids on various surfaces,^{66–70} as well as in cysteine films.³⁵

FT-IRRAS measurements further confirm the protonation of the amino group. The asymmetric deformation band of NH_3^+ at 1610 cm^{-1} and the symmetric deformation band at 1513 cm^{-1} increase in intensity at higher coverage. Tillotson et al.⁷¹ calculated that glycine adsorbs on rutile (110) with the amino group forming hydrogen bonds, stabilizing NH_3^+ . Similarly, Pantaleone et al.³⁶ found that the zwitterionic form is energetically close to the deprotonated form, even in the absence of water or surface defects. In our spectra, the NH_2 deformation band appears as a shoulder at 1550 cm^{-1} .^{72–75} These findings indicate that cysteine can adsorb on the surface

Table 1. Vibration Frequencies Assignment in Figure 3^a

Assignment	Experiments		Theory			
	Wavenumber	Reference	DP-($\text{O}_{\text{Ti}}\text{O}-\text{HO}_{\text{br}}-\text{N}_{\text{Ti}}+\text{NH}-\text{O}_{\text{br}}-\text{ni}$)	DP-($\text{O}_{\text{Ti}}\text{O}_{\text{Ti}}-\text{ni}-(\text{HS}-\text{HO}_{\text{br}})$)	biDP-($\text{O}_{\text{Ti}}\text{O}-\text{HO}_{\text{br}}-\text{ni}-(\text{S}_{\text{Ti}})$)	ZW-($\text{O}_{\text{Ti}}\text{O}_{\text{Ti}}-\text{ni}-(\text{SH}-\text{O}_{\text{br}})+\text{H}_2\text{O}$)
$\nu\text{C}=\text{O}$	1670	S4–S9	1622	—	1526	—
$\delta_{\text{asym}}\text{NH}_3^+$	1610	S5–S7	—	—	—	1582
$\nu_{\text{asym}}\text{COO}^-$	1585	S4–S9	—	1502	—	1553
δNH_2	1550	S5–S7	1561	1586	1608	—
$\delta_{\text{sym}}\text{NH}_3^+$	1513	S5–S7	—	—	—	1431
δCH_2	1472	S6,S7	1418	1424	1392	1472
$\nu_{\text{sym}}\text{COO}^-$	1363	S4–S9	—	1395	—	1376

^aComputed values are reported for the three most stable deprotonated configurations and the zwitterionic form. Modes that are absent in a given structure are indicated with a dash (—).

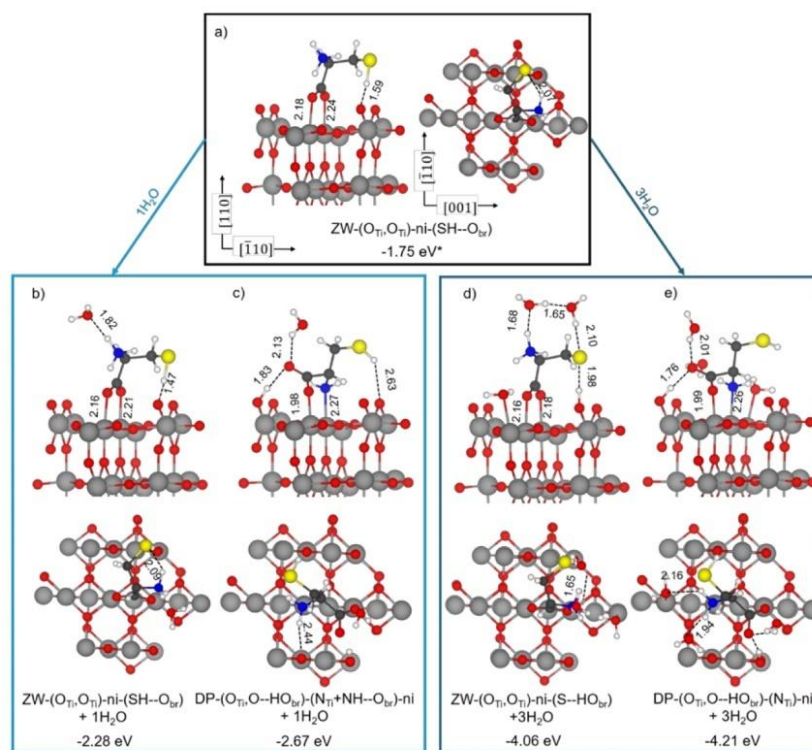


Figure 4. Structures of zwitterionic cysteine adsorbed on the rutile $\text{TiO}_2(110)$ surface in (a) dry and (b,d) “hydrated” conditions, compared with the most stable deprotonated cysteine (c,e) $\text{DP}-(\text{O}_{\text{Ti}}\text{O}-\text{HO}_{\text{br}})-(\text{N}_{\text{Ti}}\text{NH}-\text{O}_{\text{br}})-\text{ni}$. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds and other electrostatic interactions. Adsorption energies (in eV) calculated with PBE-D3+U and relevant bond lengths (values in Å) are reported. (*) For the $\text{ZW}-(\text{O}_{\text{Ti}}\text{O}_{\text{Ti}})-\text{ni}-(\text{SH}-\text{O}_{\text{br}})$, the adsorption energy values are calculated with PBE-D3 without Hubbard U.

in either a deprotonated or zwitterionic configuration. To gain deeper insights into this behavior, we performed theoretical calculations to evaluate the stability of the zwitterionic form of cysteine. Specifically, we investigated the possibility that isolated cysteine molecules on the rutile (110) surface slab model are adsorbed in a zwitterionic configuration (zwitterionic cysteine, ZW), where the proton from the carboxylic group is transferred to the amino group rather than to the surface. If the amino group becomes protonated, it cannot bind to a surface Ti_{5c} atom; therefore, the most stable configuration of the DP form is not considered. To have a protonated amino group ($-\text{NH}_3^+$), the anchoring groups are expected to be the two carboxylate O atoms coordinated to two surface Ti_{5c} atoms in a bidentate fashion, as shown in Figure 4a for $\text{ZW}-(\text{O}_{\text{Ti}}\text{O}_{\text{Ti}})-\text{ni}-(\text{SH}-\text{O}_{\text{br}})$. This configuration was localized as a minimum energy structure; however, our simulations show it to be less stable than the most favored DP (O)-(N) (i.e., $\text{DP}-(\text{O}_{\text{Ti}}\text{O}-\text{HO}_{\text{br}})-(\text{N}_{\text{Ti}}+\text{NH}-\text{O}_{\text{br}})-\text{ni}$ in Figure 1b) by +0.51 eV (Table S1). An increase in the stability of the ZW form is expected by some water solvation. Although cysteine molecules are deposited under UHV conditions, the presence of trace amounts of water in the experimental chamber cannot be entirely ruled out. To investigate this possibility, we added first one water molecule to the system, forming one H-bond with the $-\text{NH}_3^+$ group as the proton donor (Figure 4b,c); however, no significant relative stabilization for ZW is observed (with an energy difference with respect to the DP of +0.39 eV). Therefore, we decided to add three water molecules (Figure

4d,e) to create the first solvation shell. The stabilization of the zwitterionic cysteine is now far larger than the $\text{DP}-(\text{O})-(\text{N})$ structure solvated by three water molecules (in Figure 4c), resulting in an adsorption energy difference between the two of +0.15 eV. Therefore, under slightly “hydrated” conditions, ZW and DP forms become competitive and could simultaneously be present on the surface. Water contamination is a well-studied phenomenon in UHV. Despite careful sample preparation, water can still be introduced onto the surface during the evaporation process using a load lock at 10^{-9} mbar and a gas line at 10^{-5} mbar, as well as from the cysteine powder itself.^{76,77}

A comparison of the XPS characterization of adsorbed zwitterionic cysteine with the deprotonated structures (Table S4) reveals two key differences compared with the DP structures. First, the αC CLS shifts to higher binding energies by approximately 1 eV. Second, and more significantly, a new chemical environment appears, corresponding to the NH_3^+ group, with its CLS shifting by as much as 3.5 eV to higher binding energies. This shift is far from the experimental results of 1.5 eV, but this can be explained by the inaccurate screening of the proton charge at the N site, given by our choice to model the polarizing environment through the presence of a few water molecules. However, the CLS we computed for the isolated molecule in the zwitterionic form vs the neutral one is in good agreement with that already reported in previous theoretical studies.^{38,39} Finally, as done for the deprotonated configurations, we also performed a charge analysis and NCI

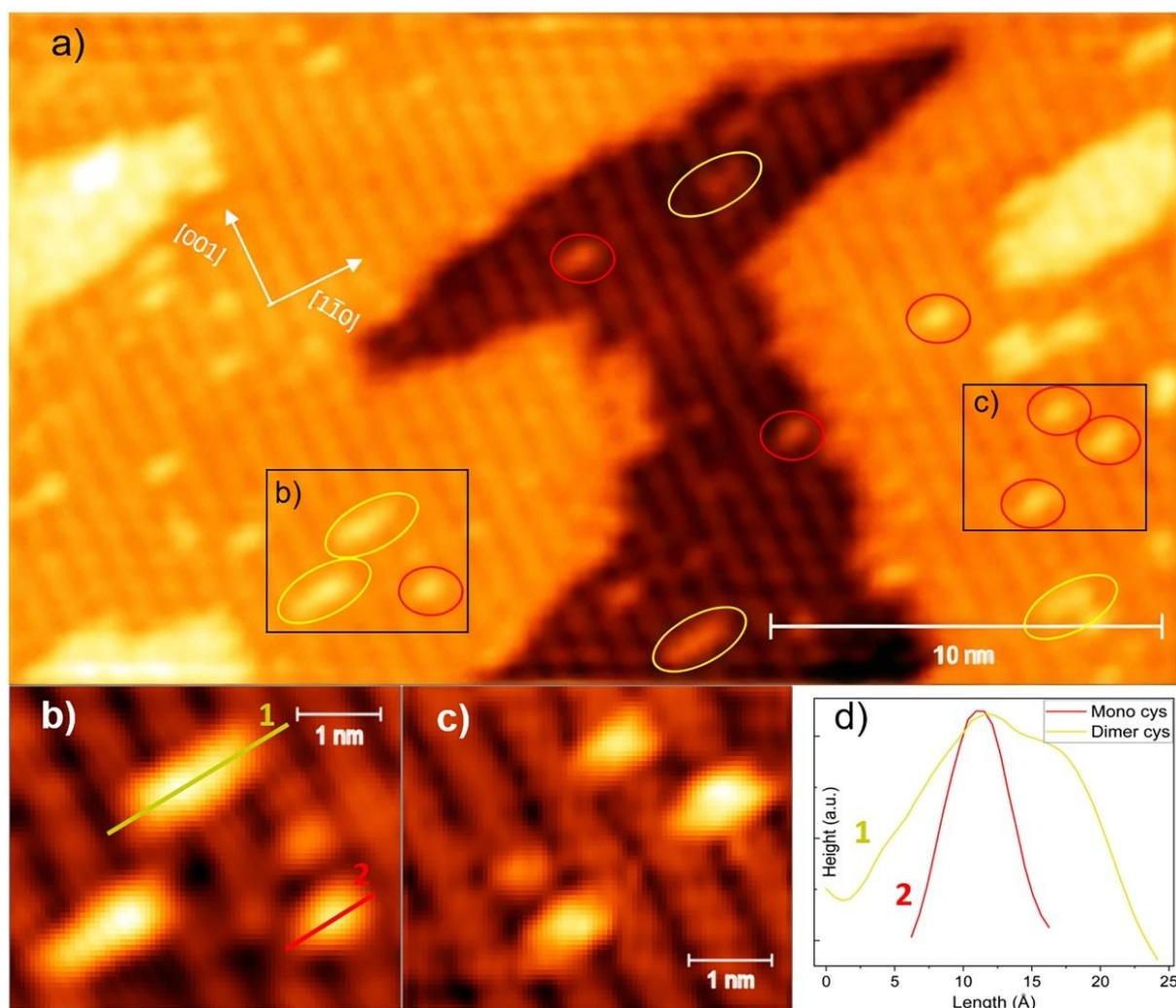


Figure 5. (a) STM image of the rutile (110) surface after dosing 0.1 L of cysteine at room temperature. 30×18 nm; image taken with 1.7 V of bias voltage and 0.3 nA current. (b,c) Magnification; (d) dimer and monomer line scans.

analysis for the zwitterionic configuration with one water molecule (Table S8 and Figure S8). Additionally, we computed the vibrational frequencies of this model structure in Figure 4b, as reported in Table 1. The computed vibrational vectors reproduce both the asymmetric and symmetric bending modes of the NH_3^+ group observed experimentally, although one must notice that the associated calculated frequencies are both systematically red-shifted with respect to the experimental bands, likely as a consequence of the use of U-corrected standard DFT instead of a hybrid DFT method and the poor screening of the positive charge in the calculation.

Cysteine Dimerization. To gain deeper insight into the adsorption geometry and surface morphology of cysteine in TiO_2 , we conducted an STM study. The rutile (110) surface has been extensively explored in numerous STM studies. It exhibits alternating bright rows of 5-fold-coordinated titanium atoms (Ti_{5c}) along the [001] direction separated by darker regions corresponding to bridging oxygen rows (O_{br}).¹² Previous STM studies have shown that carboxylic acids preferentially adsorb on top of bright Ti_{5c} rows, typically via

bridging configurations involving two adjacent Ti_{5c} atoms. Alternative adsorption sites involving vacancies have also been suggested under certain conditions.^{78,79} Qiu and Barteau⁸⁰ studied glycine adsorption on rutile TiO_2 (110) using STM and found that at higher coverages, glycine forms a (2×1) structure, binding to Ti_{5c} atoms. They suggested that the acidic proton migrates to the amino group, forming zwitterionic species, similar to cysteine adsorption. Our spectroscopy results indicate that cysteine adopts a similar bridging geometry, likely in either (O,O) or (O)-(N) configurations.

Figure 5a shows the STM image of the adsorption of 0.1 L of cysteine on rutile (110). This image enables the identification of individual adsorbates, each with an approximate size of 6.4 ± 0.3 Å. In the magnified view (Figure 5c), individual adsorbates are distinctly observed on top of the Ti_{5c} row (bright rows), further supporting a bridging configuration [(O,O), (O)-(N), or (O)-(S)]. These findings strongly support the FT-IRRAS, XPS results, and the DFT calculations.

The features marked by yellow circles exhibit a total length of 15 ± 1 Å, in which it is possible to distinguish two smaller

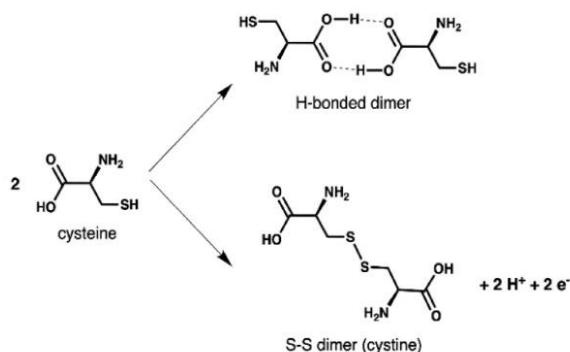
components each measuring 7.8 ± 0.7 Å. These features likely correspond to cysteine dimers, with each smaller unit slightly exceeding the size of an individual cysteine molecule. Across all STM images acquired under the same conditions, dimers are observed with an approximate frequency of one for every four individual adsorbates (see Figure S9). This dimerization behavior has been previously observed for larger organic molecules on rutile (110) at low coverages. For instance, Schnadt et al.⁸¹ found that although isonicotinic acid is able to adsorb on rutile (110) as a stable monomer, it was possible to observe dimers and even tetramers of these molecules in STM images. They attributed this tendency of dimerization to a ring interaction. The formation of amino acid dimers on different surfaces is also well-documented in the literature. A review article⁸² describes the dimerization process across various amino acids, such as serine^{83,84} and methionine,^{85,86} on different metal substrates like single-crystalline copper, gold, and silver surfaces.

Cysteine's ability to form dimers on different surfaces has been extensively studied both experimentally and computationally.^{87–89} Well-known for its disulfide bonding, cysteine is crucial for the structural stability of proteins.⁹⁰ Interestingly, cysteine dimerization is not limited to biological systems or surface interactions; it also occurs rapidly in aqueous solutions. Research shows that about 11% of cysteine molecules form dimers upon dissolving, with complete conversion to cystine occurring within 6 days, highlighting its swift oxidation in water.⁹¹

From a computational point of view, cysteine dimer formation has been reported during the equilibration phase of some molecular dynamics simulations with ReaxFF³⁹ at high zwitterionic cysteine coverage and in the second adsorption layer only. These simulations started from a cysteine droplet far from the surface; therefore, it is not clear whether the dimerization took place in the gas-phase droplet or after reaching the proximity of the surface. In order to gain some further insights into the energetics of dimer formation, we have performed a set of DFT calculations, where we considered both H-bonded and S–S dimers (Scheme 2).

The H-bonded dimers involve the carboxylic acid functionality of two cysteine molecules, and their formation inhibits the deprotonation to carboxylates and the coordination of carboxylate O atoms to surface Ti_{sc} atoms. As a result, H-bonded dimers must establish different types of interactions with the surface, such as amino N atom coordination and thiol

Scheme 2. Cysteine H-Bonded (Top) and S–S (Bottom) Dimers Formation



S coordination to surface Ti_{sc} atoms. We have evaluated both possibilities, as shown in Figure S6a,b. However, the adsorption energies are far lower than those computed for two adsorbed DP cysteines in close proximity (-3.21 vs -4.86 eV, reported in Figure S4 and Table S3). Therefore, we discard this possibility and conclude that H-bonded dimers cannot be formed on the surface since carboxylic O atoms prefer to form a coordinative bond with surface Ti atoms. The S–S dimers impose some structural constraints, but they do not inhibit adsorption by carboxylated O atoms or by amino N atoms to surface Ti atoms. To support this, we computed the molecular electrostatic potential (MEP) map of the doubly deprotonated S–S dimer (Figure S5), identifying four electron-rich regions corresponding to the two $-\text{COO}^-$ and two $-\text{NH}_2$ groups. The carboxylates exhibit a higher electron density due to the extra electrons localized on the oxygen atoms after deprotonation. The disulfide (S–S) bridge shows intermediate character and is not expected to act as a binding site on the polar TiO_2 surface. Therefore, the $-\text{COO}^-$ and $-\text{NH}_2$ groups are the most likely binding sites, interacting with positively charged Ti atoms. These dimers could adsorb lying along the [001] or the [110] directions (in Figure 6). In the latter case, they must bridge over a row of surface O atoms. We investigated both options and obtained adsorption energies that are larger (in the range between -3.87 and -4.21 eV) than for the H-bonded dimers but still quite lower than for two adsorbed DP cysteines in close proximity (-4.86 eV, Figure S4). There is indeed an energy cost to form S–S dimers since this reaction causes oxidation of the cysteine molecules (oxidation state of the S atom goes from -2 to -1). Therefore, the TiO_2 surface becomes reduced and protonated, as a consequence of the SH dissociation. We also considered the possibility of a molecular H_2 release instead of surface reduction; however, this results in an even less exothermic process (-3.13 eV). All of the calculated adsorption energy values are shown in Table S7. Additionally, the results of the charge analysis and NCI analysis are presented in Table S8 and Figure S8, respectively.

Finally, we evaluated the possibility of S–S dimer dissociation on the surface (Figure S7) for the S–S dimer [001] (O)-(N), but this process is found to be largely endothermic by $+2.32$ eV. Therefore, we conclude that S–S dimers do not form after monomer adsorption on the surface but are either present in the cysteine powder or form in the gas phase. Once they reach the surface, they remain stable and do not dissociate. Cysteine oxidation to cystine has been described in numerous studies, and cystine has been found present in multiple cysteine samples as it spontaneously oxidizes in the presence of O_2 or water.^{91–93}

The theoretical spectroscopic characterization based on CLSs of the adsorbed cysteine S–S dimer [001] (O)-(N) (see Table S4) reveals no significant differences from what we reported above for the deprotonated monomeric configurations DP (O)-(N) and DP (O,O) for all investigated atoms. This is because the S 2p CLSs of the S–S group are very close to those of the SH one. Only minor differences can be noticed for the O 1s CLSs of the H-bonded O atom (O–HO_{br}).

CONCLUSIONS

This study presents a comprehensive exploration of cysteine adsorption on the rutile $\text{TiO}_2(110)$ surface through a combined experimental and theoretical approach. Our results indicate that the bidentate (O)-(N) binding configuration is more stable than the previously proposed (O,O) bridging

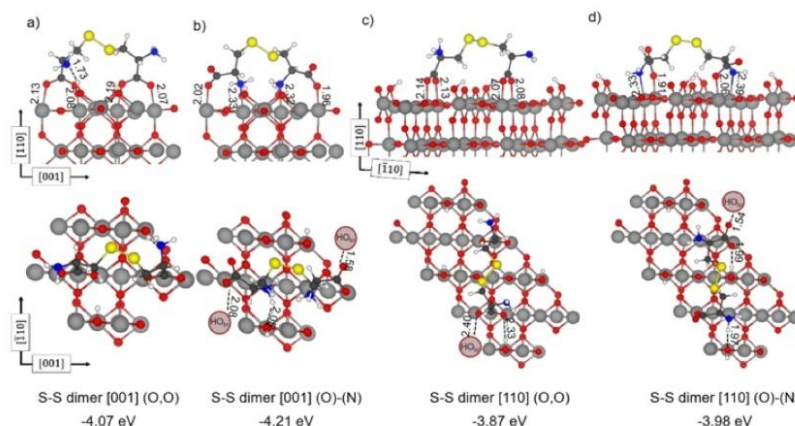


Figure 6. Structures of S–S bonded cysteine dimers adsorbed on the rutile $\text{TiO}_2(110)$ surface along the (a,b) $[001]$ and (c,d) $[110]$ directions. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds and other electrostatic interactions. Adsorption energies (in eV) calculated with PBE-D3+U and relevant bond lengths (values in Å) are reported.

mode, which had been considered the global minimum in previous studies.^{36,37}

Additionally, we identified a previously unreported (O)-(S) binding geometry, demonstrating that sulfur can chemisorb without breaking the C–S bond. This finding explains the low binding energy observed by Ataman et al. and challenges earlier assignments that assumed dissociative adsorption.³⁴ Our XPS and FT-IRRAS results, supported by solvated DFT models, also confirm that cysteine becomes a zwitterionic form when a minimal hydration shell forms, providing experimental validation for trends previously predicted for amino acids on TiO_2 surfaces. Finally, STM imaging corroborates our findings by directly visualizing both monomeric and dimeric arrangements, the latter stabilized by intermolecular disulfide bonds, species that had until now only been proposed by ReaxFF simulations.³⁹

Overall, our study clarifies how cysteine, a multifunctional amino acid, binds to the rutile $\text{TiO}_2(110)$ surface. These atomistic insights serve as a foundation for understanding the adsorption behavior of larger biomolecules such as peptides and proteins, whose interactions with TiO_2 surfaces are critical in a variety of technological applications. This knowledge is key for developing surface functionalization strategies that can tailor the TiO_2 properties for specific applications. In biomedicine, this can guide the design of coatings and implants with predictable biomolecular interactions. In catalysis and environmental technologies, it can help to enhance photocatalytic performance, where surface chemistry and the adsorption of organic molecules play a central role.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/jacs.5c07119>.

Crystal preparation methods; cysteine evaporation details; experimental procedures for X-ray photoelectron spectroscopy (XPS); scanning tunneling microscopy (STM); and Fourier-transform infrared reflection absorption spectroscopy (FT-IRRAS); thickness estimation procedure; detailed computational methodology including density functional theory (DFT) calculations, adsorption energy evaluations, and core-level shift

calculations; additional figures and tables illustrating surface characterization, calculated binding geometries, adsorption energies, and core-level shifts (PDF)

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All authors have given approval to the final version of the manuscript.

Notes

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ABBREVIATIONS

TiO₂, Titanium dioxide; Cys, cysteine; XPS, X-ray photoelectron spectroscopy; FT-IRRAS, Fourier-transform infrared reflection absorption spectroscopy; STM, scanning tunneling microscopy; DFT, density functional theory; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; CLS, core-level shift; LEED, low-energy electron diffraction; DP, deprotonated; ZW, zwitterionic

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5: Adsorption and Sulphur-Selective Photooxidation of Cysteine on Anatase TiO₂(101)

We have studied the adsorption of cysteine on anatase TiO₂(101) and subsequently investigated its photooxidation behavior. Anatase was selected for these experiments due to its higher quantum efficiency and superior ability to generate reactive oxygen species under ultraviolet illumination compared to rutile (130). Among its low index facets, the (101) surface is not only the most thermodynamically stable but also the one predominantly exposed in anatase nanoparticles used in environmental remediation and antimicrobial coatings (34, 36). Its surface arrangement consists of fivefold-coordinated Ti atoms (Ti_{5c}), twofold-coordinated oxygen atoms (O_{2c}), and a saw-tooth topography with reactive step edge. In addition, anatase (101) contains fewer surface oxygen vacancies than rutile (110) and displays distinct charge trapping behaviour (37, 131) factors that influence adsorption geometries and ultimately photocatalytic reactivity.

While cysteine adsorption on rutile TiO₂(110) has been characterized in considerable detail, including our own previous work (20), no experimental information existed on cysteine adsorption on anatase (101). This gap is significant because theoretical studies suggest notable differences between the two TiO₂ polymorphs. Rutile (110) tends to stabilize bidentate (O,O) binding of amino acids, whereas anatase (101), owing to its larger Ti_{5c}-Ti_{5c} spacing, has been predicted to favor mixed (O,N) configurations for small amino acids such as glycine (44, 57). For cysteine specifically, calculations have proposed that both (O,O) and (O,N) modes may be stabilized on anatase (101), with hydrogen bonding and thiol interactions contributing to the overall adsorption energy. Yet, until now these predictions had never been verified experimentally.

Using STM we show that cysteine adsorbs on anatase TiO₂(101) predominantly in configurations spanning two surface titanium sites, consistent with a bridging bidentate adsorption geometry in

which the molecule sits on top of two Ti_{5c} atoms. A preferential adsorption at step edges is observed, reflecting the enhanced reactivity of undercoordinated titanium sites, as previously reported for other molecular adsorbates on anatase $\text{TiO}_2(101)$ (49, 132, 133).

XPS and FT-IRRAS provide chemical evidence for the nature of these adsorption configurations. Contrary to the adsorption on rutile $\text{TiO}_2(110)$, the infrared spectra of cysteine adsorbed on anatase $\text{TiO}_2(101)$ are dominated by the C=O stretching vibration. XPS reveals a high abundance of neutral NH_2 species, with only a minor contribution from protonated NH_3^+ . In addition, sulphur is detected in both thiol (S-H) and thiolate states (S-Ti), demonstrating direct sulphur interaction with surface titanium atoms. The relative proportion of sulphur species directly bonded to titanium is higher on anatase $\text{TiO}_2(101)$ than on rutile $\text{TiO}_2(110)$.

Taken together, the spectroscopic data point to a larger fraction of adsorption configurations involving direct coordination of the amino group to surface titanium atoms, consistent with the dominance of NH_2 species and the reduced presence of NH_3^+ . At the same time, the increased contribution of S-Ti bonding reflects a higher population of adsorption geometries in which the sulphur atom directly participates in surface coordination. This behavior is consistent with the larger Ti-Ti separation on the anatase $\text{TiO}_2(101)$ surface compared to rutile $\text{TiO}_2(110)$, which facilitates adsorption geometries requiring a greater spatial separation between coordinating atoms, such as configurations involving simultaneous nitrogen and sulphur coordination. DFT calculations support this interpretation and identify two nearly degenerate, energetically favored geometries: a molecular configuration with coordination via nitrogen and sulphur, denoted as M(N,S), and a deprotonated configuration involving carboxylate oxygen and amino nitrogen coordination, $\text{DP}_{\text{COOH}}(\text{O},\text{N})$. The small NH_3^+ contribution observed in the N 1s spectra indicates

the presence of a minor fraction of zwitterionic adsorption configurations. DFT calculations exclude stable ZW(O,O) binding and instead support a limited contribution from ZW(O,S) configurations on anatase TiO₂(101).

Photocatalytic oxidation forms the central theme of this chapter. Upon exposure to UV light in the presence of air, titanium dioxide is known to generate reactive oxygen species, including hydroxyl radicals and superoxide, which can initiate oxidative transformations in organic molecules (134, 135). Cysteine is particularly susceptible to oxidation because of its thiol functional group. In biological and electrochemical environments, cysteine oxidation has been reported to follow multiple pathways, depending strongly on local conditions, pH, and oxidizing agents, with stepwise oxidation sequences observed in some aqueous and electrochemical systems (60, 136).

XPS measurements performed after controlled UV exposure reveal a clear temporal evolution of sulphur oxidation states on anatase TiO₂(101). Upon illumination, the original S-H and S-Ti components progressively disappear, while new sulphur peaks respectively emerge at binding energies of approximately 166.5 eV and 168.7 eV. The higher binding energy component at 168.7 eV is assigned to fully oxidized sulphur species, corresponding to sulfonic acid or sulfonate-like groups (-SO₃H / -SO₃⁻), whereas the feature at 166.5 eV is attributed to sulphur in mixed or intermediate oxidation states. Full conversion of sulphur to the highest oxidation state is achieved within the first 15 minutes of UV exposure in air, after which no further spectral evolution is observed in XPS spectra.

Throughout the oxidation process, the nitrogen chemical environment remains unchanged, indicating that the amino group does not participate directly in the photocatalytic reaction. Changes in the C 1s region are limited to secondary contributions associated with hydrocarbon

contamination and the appearance of C–SO_x related components accompanying sulphur oxidation. When the same UV illumination experiments are performed under UHV conditions in the absence of oxygen, no sulphur oxidation is detected, demonstrating that molecular oxygen is essential for the reaction pathway.

DFT calculations provide a mechanistic framework for the experimentally observed stepwise sulphur oxidation on anatase TiO₂(101). The reaction is initiated by physisorption of molecular O₂ at a Ti_{5c} site, followed by a photoactivated step in which O₂ is converted into a chemisorbed superoxo species while the cysteine -SH group deprotonates and sulphur is oxidized from (-2) to (-1). In this step, the photoexcited electron localizes on O₂ and the hole on sulphur, with only a small electronic energy cost. The superoxo intermediate is subsequently reduced by conduction band electrons from bulk anatase, forming a peroxo species that is stabilized by protonation to yield a surface hydroperoxo (-OOH) intermediate. This highly reactive species drives further sulphur oxidation, preferentially via direct oxygen transfer to form an S=O group, which is energetically favored over stepwise proton and OH transfer. Completion of the oxidation requires adsorption of a second oxygen molecule, coupled with OH transfer to form a -SOOH intermediate, followed by additional reduction and oxygen transfer steps that yield the fully oxidized sulfonic acid (-SO₃H) product. Overall, the mechanism involves one photon, two O₂ molecules, and two bulk electrons to fully oxidize one cysteine thiol group, while the amino functionality remains chemically inactive throughout the process.

Within this thesis, this chapter establishes anatase TiO₂(101) as a model system to study amino acid adsorption and UV-driven photocatalytic reactivity. We combine STM, XPS and FT-IRRAS with DFT calculations to obtain a molecular-level picture of the system. This allows us to describe

how cysteine adsorbs on anatase and to show for the first time that it undergoes UV-induced photocatalytic oxidation on anatase $\text{TiO}_2(101)$.

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Adsorption and Sulphur-Selective Photooxidation of Cysteine on Anatase TiO₂(101)

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ABSTRACT: Understanding how multifunctional amino acids interact with photocatalytic oxide surfaces is essential for controlling their interfacial redox chemistry. Here we combine scanning tunneling microscopy (STM), X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared reflection absorption spectroscopy (FT-IRRAS), and density functional theory (DFT) calculations to elucidate the adsorption geometry and photooxidation mechanism of cysteine on anatase TiO₂(101). STM reveals a bridging adsorption motif at surface Ti sites. XPS and FT-IRRAS demonstrate that adsorption favors configurations in which the amino group remains largely unprotonated, enabling direct coordination of both nitrogen and sulphur to Ti centers. DFT calculations identify two adsorption configurations with comparable stability, a molecular M(N,S) structure, where cysteine is bound to the surface through nitrogen and sulphur, and a partially deprotonated DP_{COOH}(O,N) structure, where it adsorbs through a carboxylic oxygen and nitrogen. Upon UV irradiation in air, cysteine undergoes highly selective photooxidation at the sulphur site, while the carbon and nitrogen moieties remain largely unaffected. XPS reveals stepwise oxidation and transformation of sulphur from thiol to fully oxidized sulfonic acid (-SO₃H), through distinct intermediate states. DFT calculations rationalize this selectivity by identifying a surface-mediated mechanism in which activation of molecular oxygen promotes sequential sulphur oxidation, consistent with the experimentally observed XPS data. These results demonstrate that adsorption geometry and local coordination environment at oxide interfaces dictate specific photooxidation pathways, providing a molecular level framework for controlling selective transformations of multifunctional organic molecules on photocatalytic surfaces.

INTRODUCTION

Titanium dioxide (TiO₂) is one of the most widely studied photocatalytic materials due to its chemical stability, low cost, non-toxicity, and ability to generate reactive oxygen species (ROS) under UV illumination. These ROS, including hydroxyl radicals (·OH) and superoxide (O₂⁻), enable the oxidative degradation of organic pollutants such as alcohols, dyes, and volatile organic compounds, as well as the inactivation of microorganisms and viruses (1-6). For example, recent studies have shown that TiO₂ effectively degrades SARS-CoV-2 Spike proteins, leading to viral inactivation (7-9).

Photocatalytic oxidation of simple molecules, such as methanol, isopropanol, and formic acid, has been extensively explored on anatase (101) and rutile (110) surfaces, providing insight into surface reaction pathways (10-12). Building on those studies, understanding how biomolecules interact with TiO₂ is important for improving the performance of sustainable

photocatalytic surfaces for air purification, environmental remediation, and antiviral applications.

Among biologically relevant molecules, amino acids are particularly relevant model systems because they represent the fundamental structural units of proteins. Their adsorption behavior reflects key surface interactions, proton transfer, hydrogen bonding, and coordination to metal sites, that ultimately govern the degradation processes of biomolecules. Several studies have examined the adsorption of amino acids, including glycine, alanine, serine, glutamic acid, and others, on TiO₂ using a combination of X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared spectroscopy (FT-IR), near-edge X-ray absorption fine structure (NEXAFS), and density functional theory (DFT) (13-18). These studies established common binding configurations such as bidentate (O,O) coordination of the carboxylate group and, in some cases, mixed (O,N) interactions involving the amino group. However, the

details depend strongly on the specific TiO₂ polymorph, surface structure and the presence of water.

Cysteine represents a particularly important case because its thiol group is highly reactive and plays a key role in redox processes, protein folding, and biochemical signaling (19–21). In biological systems, cysteine oxidation follows multiple parallel pathways depending on the local environment and redox conditions (22), whereas on solid materials, including metal oxides, oxidation typically proceeds through a ROS-driven stepwise mechanism as described by Reynaud and co-workers (23). This sequential SH → SOH → SO₂H → SO₃H pathway is central to oxidative protein degradation and is highly relevant for photocatalytic surfaces (24, 25). Despite this importance, only a limited number of studies have examined cysteine adsorption on TiO₂, and most of them have focused exclusively on the rutile (110) surface.

Previous studies of cysteine adsorption on rutile TiO₂(110) generally proposed that the molecule binds through its deprotonated carboxylate group in a bridging (O,O) configuration, a geometry that is stabilized by the close match between the carboxylate O...O distance and the titanium five-fold coordinated Ti_{5c}-Ti_{5c} spacing on the rutile TiO₂(110) surface. (26–29). However, the literature contains notable inconsistencies. Ataman et al. (26) suggested additional S-Ti interactions and even partial C-S bond cleavage, whereas Muir and Idriss (28) reported only (O,O) and (O,N) geometries without sulphur involvement. Reactive force-field simulations further predicted that the thiol group may participate in hydrogen bonding or proton-transfer processes, adding uncertainty to the adsorption mechanism (30, 31). A combined STM, XPS, FT-IRRAS, and DFT study showed that cysteine adsorption on rutile is more complex than previously assumed (32). At room temperature, three adsorption geometries coexist on the surface: a bidentate carboxylate (O,O) configuration, a mixed (O,N) mode involving amino group coordination, and an (O,S) configuration in which the thiolate interacts with Ti sites without C-S bond cleavage. Cysteine can adsorb in either deprotonated or zwitterionic form, and STM revealed dimer formation even at low coverage (32).

However, the phase of the TiO₂ surface strongly influences both adsorption and photocatalytic behavior. Rutile (110) exposes rows of five-fold coordinated Ti (Ti_{5c}) and two-fold oxygen (O_{2c}) sites and surface oxygen vacancies are frequent on this surface, whereas anatase TiO₂(101) exhibits a zig-zag arrangement of Ti_{5c}-O_{2c} pairs, a higher tendency for subsurface oxygen vacancy formation, and enhanced charge separation efficiency (33–36). These structural and electronic differences lead to distinct adsorption geometries, reaction intermediates, and photochemical reactivities. For example, acetic acid has been observed to adopt mixed adsorption geometries on anatase TiO₂(101) (37). Petrik et al. reported that formic acid undergoes temperature-dependent conversion pathways on anatase TiO₂(101)

that have no direct analogue on rutile TiO₂(110), underscoring the higher configurational flexibility and reactivity of the anatase surface (38).

Theoretical studies show that anatase TiO₂(101) stabilizes (O,N) adsorption geometries more effectively than rutile (110), a trend attributed to its larger Ti_{5c}-Ti_{5c} spacing (3.79 Å compared with 2.96 Å on rutile (39, 40). For cysteine specifically, DFT predicts that both (O,O) and (O,N) configurations can be accessible on anatase, with additional stabilization arising from hydrogen bonding involving the thiol group. However, no experimental work has yet verified these adsorption modes on anatase TiO₂(101) or their photo-induced evolution under UV illumination.

The present work addresses these gaps by providing the first experimental investigation of cysteine adsorption and photocatalytic oxidation on anatase TiO₂(101). Using STM, XPS, FT-IRRAS, and DFT calculations, we identify the preferred adsorption geometries and protonation states. We further examine how UV irradiation in air drives cysteine oxidation, determine which functional groups undergo chemical transformation, identify the reaction intermediates and compare these results with our previous studies on rutile (110) surface to reveal facet-dependent reactivity of TiO₂. Understanding these processes is essential for advancing the design of photocatalytic materials for self-cleaning and antiviral applications.

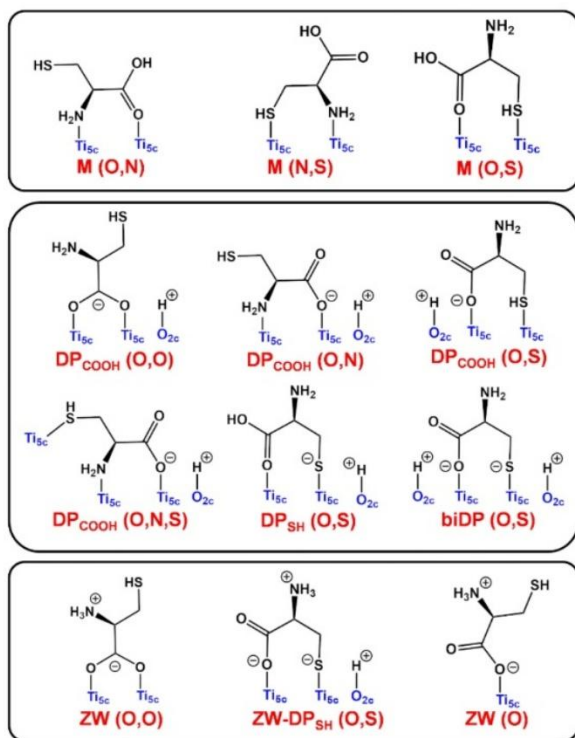
RESULTS AND DISCUSSION

In this section, we first present a systematic investigation of the adsorption configurations of cysteine on the anatase TiO₂(101) surface. This will be followed by the analysis of the photooxidation mechanism.

Nomenclature for cysteine adsorption on anatase TiO₂(101). As cysteine contains multiple functional groups and can exist in different protonation states, we first introduce a nomenclature to describe the possible adsorption configurations on the anatase surface. Specifically, we consider the following cases: molecular (M), in which the carboxylic, amino, and thiol groups are in their intact (protonated) forms; deprotonated at the carboxylic or thiol group (DP_{COOH} and DP_{SH}, respectively), where the loss of a proton leads to the formation of -COO⁻ or -S⁻; zwitterionic (ZW), in which the proton released from the carboxylic group protonates the amino group, yielding -NH₃⁺; and bideprotonated (biDP), where both the carboxylic and thiol groups are deprotonated.

Each cysteine adsorption geometry is labeled by the protonation state of the molecule, defined above, followed by a descriptor (in parentheses) indicating which cysteine atoms form covalent bonds with the TiO₂(101) surface. In all configurations considered cysteine establishes at least two distinct interactions with surface atoms. These configurations are summarized and schematically illustrated in **Scheme 1**.

Scheme 1. Cysteine adsorption modes on anatase TiO₂(101). The Ti_{5c} and O_{2c} sites indicate undercoordinated surface Ti and O atoms, respectively, which act as anchoring sites for the molecule.



Adsorption of cysteine on anatase TiO₂(101): Experimental results.

The anatase TiO₂(101) surface was prepared and characterized under ultrahigh vacuum (UHV) conditions prior to molecular adsorption. After standard cleaning procedures of sputtering and annealing, the surface structure was examined by scanning tunnelling microscopy (STM) to establish a well-defined reference state. Experimental details of the surface preparation are provided in the **Supporting Information**.

Figure 1a presents a high-resolution STM image of the anatase TiO₂(101) surface after deposition of 1 L of cysteine. The surface exhibits a terraced morphology with monatomic step edges. The bright protrusions correspond to alternating Ti_{5c}-O_{2c} pairs, which appear as periodic bright features due to electronic contrast differences. Unlike rutile TiO₂(110), where Ti_{5c} sites are imaged as bright protrusions in empty states, in anatase TiO₂(101), both Ti_{5c} and O_{2c} contribute to the observed contrast (33, 41). The crystallographic directions were assigned based on step orientations and island shapes following the approach proposed by Gong et al. (34) which relates trapezoidal island morphologies to the surface symmetry. STM image of the clean anatase TiO₂(101) surface are provided in **Figure S2**.

Individual cysteine molecules are clearly resolved on the surface. Adsorption is observed both on terraces and

preferentially along step edges, suggesting that these sites provide more favorable binding configurations compared to terraces. This adsorption behavior at step edges has been reported before by Setvin et al. (42), who demonstrated that these sites act as charge accumulation centers, enhancing their reactivity toward adsorbed molecules. Step edge adsorption has also been reported for other adsorbates such as water (43) and acetic acid (44).

Figure 1b, a magnified region of **Figure 1a**, reveals two individual cysteine molecules adsorbed on a terrace. These molecules appear as bright features, centered on top of two Ti_{5c}-O_{2c} pairs and extending towards the adjacent row. This suggests that cysteine is directly bound to two Ti_{5c} sites consistent with a bidentate bridging configuration. The portion extending toward the next row may indicate additional stabilization via hydrogen bonding with surface oxygen atoms, as illustrated in **Figure 1c**. Line scans 2 and 3, performed on one of these molecules, measure approximately 7 Å in both directions, confirming the expected molecular size of cysteine (45, 46). Line scan 3 also shows the distance between Ti_{5c}-O_{2c} pairs, measured as 7.3 Å, showing that the molecule spans approximately twice this distance, confirming its adsorption across two adjacent Ti_{5c} sites.

STM imaging alone cannot definitively distinguish between different bridging adsorption configurations, such as DP_{COOH}(O,N) or M(N,S), nor it can exclude the presence of other adsorption configurations, since all bridging configurations are expected to produce similar contrast in STM images. For this reason, the STM results are complemented by XPS and FT-IRRAS to further constrain the adsorption mode and the molecule-surface interactions.

XPS measurements were performed on the anatase TiO₂(101) surface following cysteine adsorption. Prior to cysteine evaporation, the clean sample showed no carbon, hydroxyl or water contamination. The O 1s and C 1s core level spectra and the low energy electron diffraction pattern of the clean surface can be seen in **Figure S1**. Fitting parameters for every XP spectrum are shown in **Table S3**.

The deconvoluted O 1s core level spectrum (**Figure 2a**) includes two components belonging to the TiO₂ structure that are also present in the clean spectra. The peak at 530.3 eV corresponds to lattice oxygen in TiO₂, while the second component at 531.0 eV has been attributed either to an intrinsic species within the TiO₂ lattice or asymmetry in the O 1s peak (47). On top of the anatase TiO₂(101) spectrum we plotted the rutile TiO₂(110) cysteine adsorbed spectrum of our previous study (32).

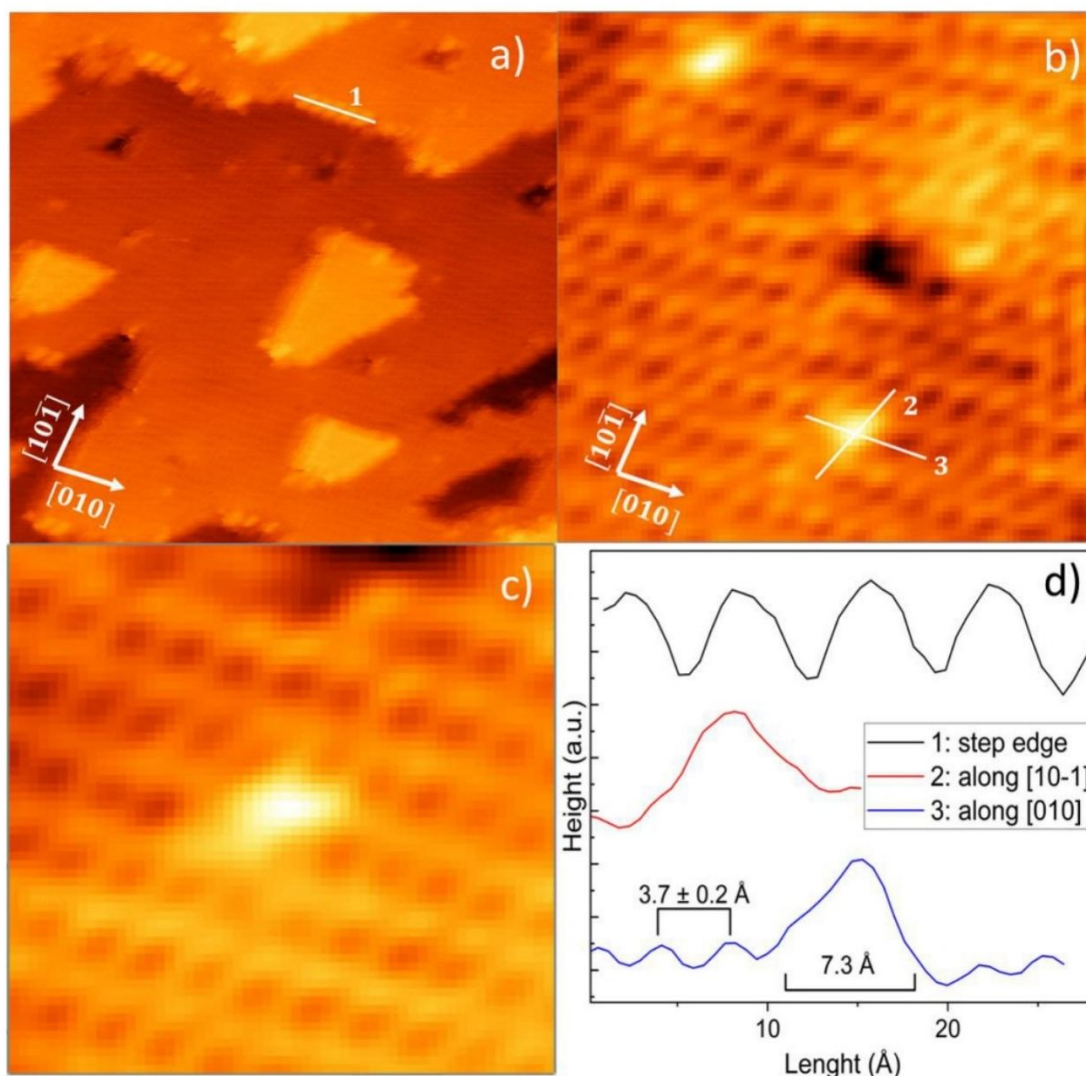


Figure 1. STM images of the anatase $\text{TiO}_2(101)$ surface after dosing 1 L of cysteine at room temperature. All images were acquired in empty state mode with bias voltages between 1-1.2 V and tunneling currents of 0.1-0.3 nA. (a) STM image after deposition of 1 L of cysteine ($28 \times 28 \text{ nm}^2$). Line scan 1 was taken across the step edge along the $[010]$ direction. (b) Magnified STM image ($5 \times 5 \text{ nm}^2$) of Figure 1a, showing two individual cysteine molecules adsorbed on the terrace. Line scans 2 and 3 were taken across these molecules. (c) Close-up STM image ($3 \times 3 \text{ nm}^2$) of a single cysteine molecule adsorbed on the anatase $\text{TiO}_2(101)$ terrace, revealing its adsorption atop two $\text{Ti}_{5c}\text{-O}_{2c}$ pairs along $[010]$ and extending toward the next row. (d) Line scans 1, 2, and 3 extracted from Figures 1a and 1b, displaying molecular dimensions and Ti_{5c} spacing.

After cysteine evaporation, a new oxygen peak appeared at 532.1 eV, characteristic of oxygen from carboxylic compounds (26, 29, 48-51). Cysteine has two distinct oxygen atoms (C=O , C-OH), which in the case of a protonated carboxylic acid would typically give rise to two O 1s peaks separated by about 1-1.3 eV, with the proton-bonded oxygen appearing at higher binding energy, often above 533 eV (49, 52, 53). In the present spectra, only a single additional O 1s contribution is resolved. While the presence of a single additional O 1s component is commonly associated with carboxylate formation, closely spaced oxygen contributions may be difficult to resolve experimentally due to intrinsic line broadening and the dominance of the intense lattice O 1s

peak. In addition, configurations involving hydrogen bonding can shift the binding energies of the carboxyl oxygen to lower values, thereby reducing the separation between the two oxygen components. As a consequence, the O 1s spectrum alone does not allow a definitive distinction between different adsorption geometries.

The deconvoluted C 1s core level spectrum, presented in **Figure 2b**, reveals three distinct carbon species, corresponding to the three inequivalent carbon atoms in the cysteine molecule. The peak at 289.0 eV, assigned to the carboxyl carbon, appears at the highest binding energy. The peak at 285.9 eV corresponds to the α -carbon ($\text{C}\alpha$), while the lowest binding energy peak at

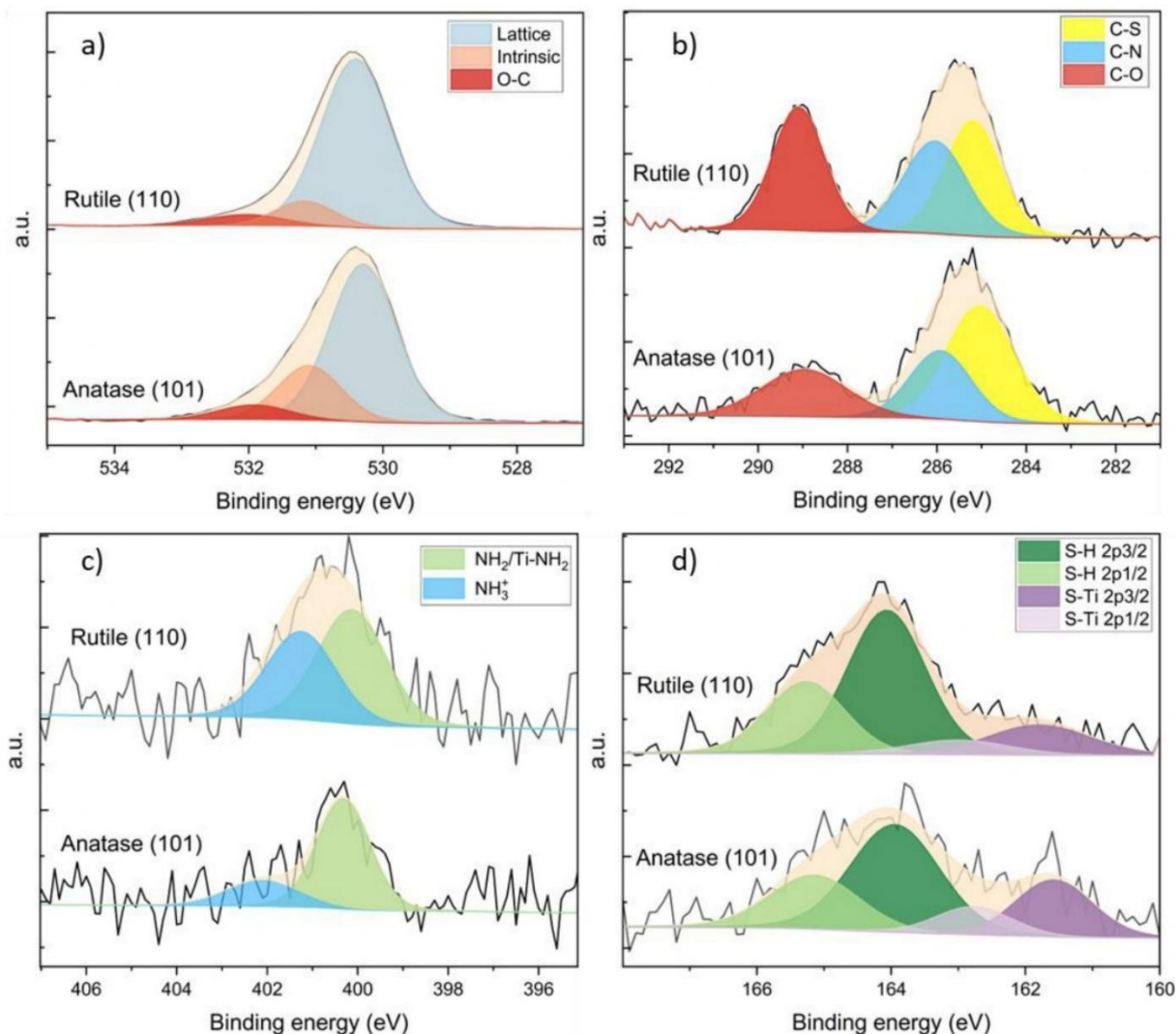


Figure 2. Deconvoluted XP spectra of 50 L of cysteine adsorbed on anatase $\text{TiO}_2(101)$. Experimental data (black lines) and deconvoluted components (colored areas) are presented for (a) O 1s, (b) C 1s, (c) N 1s, and (d) S 2p core levels. For comparison, the corresponding spectra for cysteine adsorbed on rutile $\text{TiO}_2(110)$ from a previous study are shown.

285.2 eV is attributed to the carbon bonded to sulphur (C-S) (26, 27, 54, 55). When comparing these results to those obtained for cysteine adsorption on rutile, no significant differences are observed in the C α and C-S peak positions or relative intensities. In contrast, a clear difference is observed in the intensity of the carboxyl peak. On rutile, the peak ratio among the three carbon species was approximately 1:1:1, whereas on anatase, the carboxyl peak is significantly weaker than the other two. In principle, contamination or beam-induced decomposition could alter peak ratios, but both surfaces were confirmed to be clean prior to dosing and no time dependent changes were observed in the C 1s or O 1s regions after X-ray irradiation, excluding these effects. Similar attenuations of the high binding energy carboxyl component have been reported for other amino acids, such as aspartic acid on Ni(100) (56), serine on Cu(110) (57), alanine on Ni(111) (58), and p-aminobenzoic acid on TiO_2 (59), and were consistently attributed to

photoelectron diffraction, which selectively reduces the detected intensity of specific chemical environments (60, 61).

Figure 2c displays the N 1s core level spectrum, where two distinct components were fitted, exhibiting a peak splitting of approximately 2 eV. This peak position and splitting have been previously reported for various amino acids and structurally related molecules adsorbed on different surfaces (57, 59, 62, 54, 63–66). The higher binding energy peak at 402.2 eV is attributed to the protonated amino group ($-\text{NH}_3^+$), while the lower binding energy peak at 400.3 eV corresponds to the neutral amino group ($-\text{NH}_2$), which may or may not be coordinated to Ti, as previously demonstrated in rutile by the spectroscopic characterization of CLSs (core level shifts) (32).

A clear difference between anatase and rutile in the N 1s region is the amount of $-\text{NH}_3^+$ species. The $-\text{NH}_3^+$ peak is

much stronger on rutile, even though the overall adsorbed amount is similar on both surfaces. This points to a difference in adsorption geometry rather than coverage. On anatase, the amino group likely interacts more directly with the TiO_2 surface (via N-Ti coordination), which would make protonation less favorable and reduce the $-\text{NH}_3^+$ contribution. We examine these geometries in more detail in the theoretical section below.

Figure 2d shows the deconvoluted XP spectra of the S 2p core level, which reveal two distinct sulphur species with a peak splitting of 2.3 eV. The lower binding energy peak at 161.6 eV is assigned to sulphur coordinated to Ti_{5c} sites, while the higher binding energy peak at 163.9 eV is associated with the thiol ($-\text{SH}$) group in cysteine. A comparison of the relative peak intensities shows that the S-Ti contribution is more pronounced on anatase than on rutile, indicating that a larger fraction of cysteine molecules adsorb with sulphur directly bonded to the surface. This trend is consistent with the larger Ti-Ti spacing on anatase, which can accommodate sulphur coordination with reduced geometric strain. This behaviour is discussed further in the theoretical section below.

We have further investigated the sample using FT-IRRAS to probe the vibrational modes of cysteine adsorbed on anatase. **Figure 3** shows the evolution of the spectra with increasing cysteine coverage on anatase, together with a direct comparison to rutile. If bridging bidentate (O,O) coordination dominates the adsorption of cysteine, two distinct vibrational bands corresponding to the asymmetric (ν_{asym}) and symmetric (ν_{sym}) stretching modes of the OCO should be observed. Previous studies on carboxylic acids, such as formic acid on anatase $\text{TiO}_2(101)$ and serine on commercial anatase as well as other oxide surfaces indicate that these bands typically appear in the range of 1600 - 1550 cm^{-1} (ν_{asym}) and 1410 - 1370 cm^{-1} (ν_{sym}) (67-69). On the other hand, adsorption geometries that keep the carbonyl bond ($\text{C}=\text{O}$), such as molecular adsorption, are expected to give rise to a distinct $\text{C}=\text{O}$ stretching vibration in the 1700 cm^{-1} region. We observe a prominent band at 1700 cm^{-1} that is assigned to the carbonyl ($\text{C}=\text{O}$) stretching mode, in good agreement with literature values for carbonyl vibrations (70, 71). At 1590 cm^{-1} and 1406 cm^{-1} , we identify the $\nu_{\text{asym}}(\text{OCO})$ and $\nu_{\text{sym}}(\text{OCO})$ bands, respectively, aligning well with reported values for deprotonated carboxylic groups (15, 67-69, 72). Xu et al. (68) reported a $\nu_{\text{asym}}(\text{OCO})$ mode at 1598 cm^{-1} and a $\nu_{\text{sym}}(\text{OCO})$ mode at 1362 cm^{-1} for formic acid adsorption, while Pászti and Guzzi (72) found a $\text{C}=\text{O}$ stretching band at 1712 cm^{-1} and asymmetric and symmetric OCO-stretching modes at 1550 cm^{-1} and 1400 cm^{-1} , respectively, for glutamic and aspartic acid adsorption on TiO_2 . In comparison, our previous study on rutile (110) revealed slightly shifted bands, with $\nu_{\text{asym}}(\text{OCO})$ at 1585 cm^{-1} and $\nu_{\text{sym}}(\text{OCO})$ at 1363 cm^{-1} (32).

In the N-H region, the $-\text{NH}_2$ deformation band is clearly observed at 1567 cm^{-1} , whereas the $-\text{NH}_3^+$ deformation

bands at 1627 cm^{-1} and 1530 cm^{-1} are much weaker (71, 73-75), indicating that $-\text{NH}_2$ species dominate with only a minor $-\text{NH}_3^+$ contribution, consistent with the N 1s XPS trend. Roddick-Lanzilotta and McQuillan (76) reported the $-\text{NH}_3^+$ asymmetric and symmetric deformation modes at $\sim 1620 \text{ cm}^{-1}$ and $\sim 1520 \text{ cm}^{-1}$, respectively. Ustunol et al (77) observed comparable assignments across a range of amino acids on TiO_2 nanoparticles: $\text{C}=\text{O}$ stretching at 1740-1710 cm^{-1} , $\nu_{\text{asym}}(\text{COO}^-)$ around 1590 cm^{-1} , and $\nu_{\text{sym}}(\text{COO}^-)$ around 1410 cm^{-1} , the $-\text{NH}_3^+$ symmetric and asymmetric deformation bands were observed approximately at 1620 cm^{-1} and 1515 cm^{-1} , respectively, while the $-\text{NH}_2$ deformation appeared at 1560 cm^{-1} . In rutile (110), the asymmetric $-\text{NH}_3^+$ deformation band is located at 1610 cm^{-1} , while the symmetric mode appears at 1513 cm^{-1} , and the $-\text{NH}_2$ deformation at 1550 cm^{-1} (32). Although the vibrational frequencies are not identical, shifts between anatase and rutile are expected due to differences in their local chemical environments.

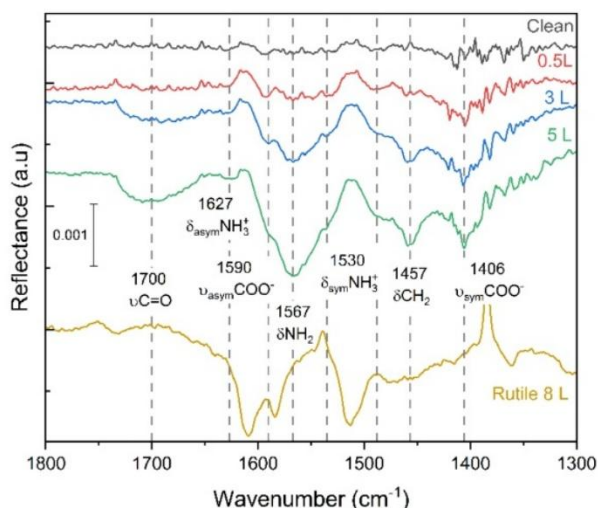


Figure 3. FT-IRRAS spectra of cysteine adsorbed on anatase $\text{TiO}_2(101)$ at room temperature for increasing coverage. The vibrational features of cysteine adsorbed on rutile $\text{TiO}_2(110)$ at 8 L coverage (yellow spectrum) are also included for comparison.

Overall, our experimental results lead to three main conclusions. First, STM imaging shows that cysteine adsorbs on top of surface Ti atoms with a bridging bidentate configuration. Second, the N 1s XPS spectrum and the N-H vibrational region in IRRAS indicate that the amino group is largely not protonated on anatase; compared with rutile, this points to adsorption configurations on anatase in which N is directly bonded to Ti. Third, the S 2p XP spectra reveal a larger contribution from sulphur species directly bonded to surface Ti atoms on anatase than on rutile.

Adsorption of cysteine on anatase $\text{TiO}_2(101)$ surface: Computational results.

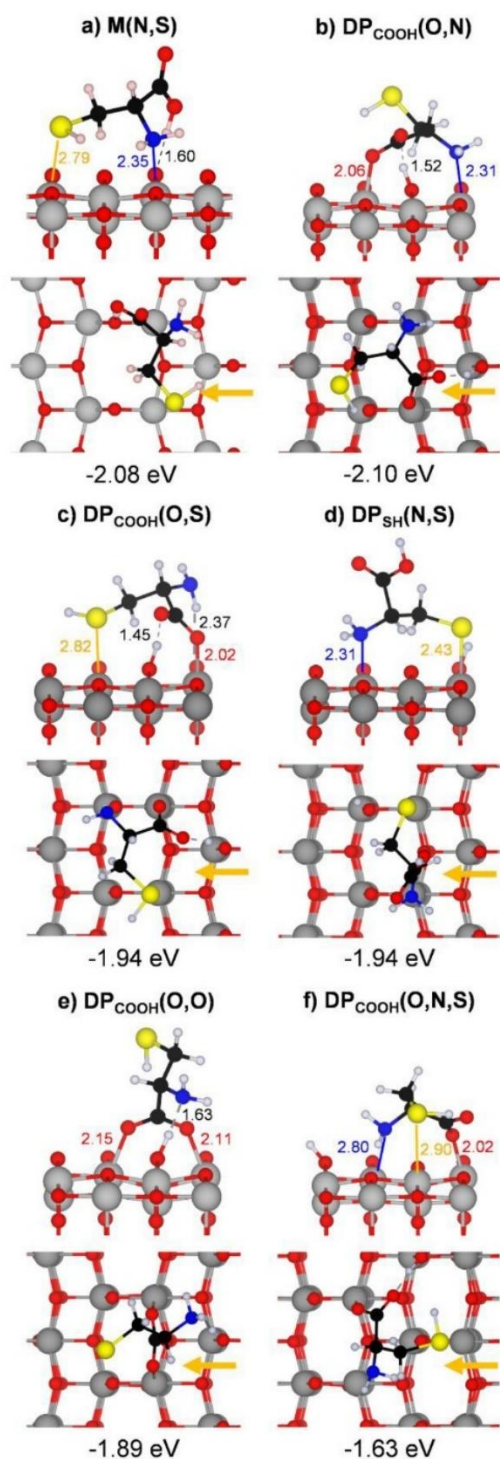


Figure 4. Side and top views of the optimized structures of the most stable molecular and deprotonated cysteine adsorption configurations on the anatase $\text{TiO}_2(101)$ surface, calculated at the PBE+D3+U level. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds. Adsorption energies (in eV) are reported below each structure, and selected bond lengths (in Å) are indicated. For clarity, only a portion of the supercell is shown. The orientation of the side view is indicated by an orange arrow in each top-view panel.

To gain deeper insight into the adsorption behavior of cysteine, we used DFT calculations to systematically investigate various adsorption modes and compare their relative energetics to identify the most stable configurations. The most relevant structures were then characterized spectroscopically by calculating core level shift (CLS) values and IR vibrational frequencies, which were directly compared with the experimental data presented above.

Molecular cysteine

The most stable molecular adsorption configuration of cysteine on anatase $\text{TiO}_2(101)$, labelled M(N,S) and shown in **Figure 4a**, is characterized by the molecule binding through dative interactions of the $-\text{NH}_2$ and $-\text{SH}$ groups to two Ti_{5c} surface sites, while the $-\text{COOH}$ group forms one hydrogen bond with a surface O_{2c} atom. The resulting adsorption energy is -2.08 eV (a negative value indicates that the adsorption is favorable). As reported in **Figure S3** several additional molecular adsorption structures were identified, with adsorption energies ranging from -1.43 to -1.89 eV.

Deprotonated cysteine

Cysteine contains two acidic groups, $-\text{COOH}$ and $-\text{SH}$, that can dissociate on a polar surface like TiO_2 . Upon adsorption, the carboxylic group typically deprotonates by transferring a proton to a nearby surface bridging oxygen atom, which results in a deprotonated carboxylate species (DP). Adsorption involves coordination of one or both carboxylate oxygen atoms with undercoordinated surface Ti_{5c} atoms. If only one carboxylate oxygen atom binds to the surface, either the amino nitrogen atom or the thiol sulphur atom can coordinate to an adjacent surface Ti_{5c} , yielding the $\text{DP}_{\text{COOH}}(\text{O,N})$ and $\text{DP}_{\text{COOH}}(\text{O,S})$ geometries, respectively, as shown in **Figures 4b** and **4c**. Among these three configurations, $\text{DP}_{\text{COOH}}(\text{O,N})$ is the most stable, with an adsorption energy of -2.10 eV, very close to that of the M(N,S) configuration (-2.08 eV), whereas $\text{DP}_{\text{COOH}}(\text{O,S})$ is less favourable (-1.94 eV). Small energy differences between the most stable DP and M structures were also reported by Pantaleone et al., see **Table S1**. We note, however, that entropic contributions (not calculated here) would slightly favour the deprotonated state over the molecular forms (39).

In the $\text{DP}_{\text{COOH}}(\text{O,N})$ structure, a third interaction can occur, in which the thiol group binds to a Ti_{5c} atom on a parallel surface row of Ti_{5c} atoms, forming the $\text{DP}_{\text{COOH}}(\text{O,N,S})$ structure (**Figure 4f**). However, due to the strain imposed by the three simultaneous interactions, this configuration is significantly less favourable (-1.63 eV) than the previously discussed adsorption modes, as evidenced by the longer N-Ti and S-Ti bond distances reported in **Figure 4f**.

When both carboxylate oxygens bind to two Ti_{5c} atoms, the $\text{DP}_{\text{COOH}}(\text{O,O})$ adsorption geometry is formed, as

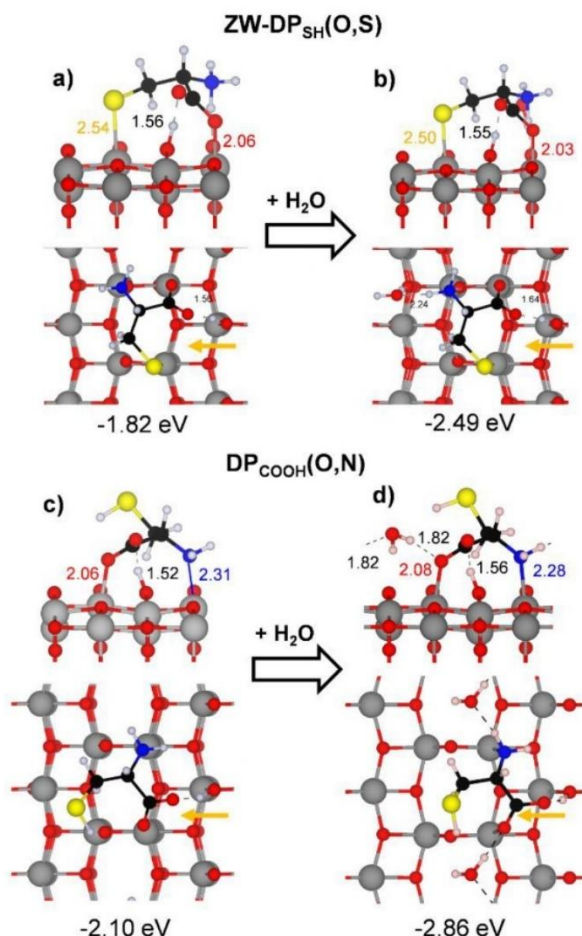


Figure 5. Side and top views of the optimized structures of the most stable zwitterionic (a,b) and deprotonated (c,d) cysteine adsorption configurations on the anatase $\text{TiO}_2(101)$ surface, calculated at the PBE+D3+U level. The right panels show the corresponding optimized structures in the presence of one interacting water molecule. The structure shown in panel c corresponds to that reported in Figure 4b. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds. Adsorption energies (in eV) are reported below each structure, and selected bond lengths (in Å) are indicated. For clarity, only a portion of the supercell is shown. The orientation of the side view is indicated by an orange arrow in each top-view panel.

shown in **Figure 4e**, with a corresponding adsorption energy of -1.89 eV.

Cysteine can adsorb without involving the carboxylic group in the surface binding, through coordination of both the amino nitrogen and thiol sulphur atoms to surface Ti_{5c} atoms, giving rise to the $\text{DP}_{\text{SH}}(\text{N},\text{S})$ adsorption mode shown in **Figure 4d**.

All optimized deprotonated adsorption geometries are reported in **Figure S4** whereas the most stable structure within each category, highlighted in bold, is also shown in **Figure 4**.

Zwitterionic cysteine

Our experimental XPS and FT-IRRAS results indicate that cysteine can adsorb on the surface in either deprotonated or zwitterionic configurations. However, the $-\text{NH}_3^+$ signal is significantly weaker than that of $-\text{NH}_2$, indicating that the zwitterionic form is less frequent. To clarify this point, we also computed the stability of zwitterionic cysteine on the anatase $\text{TiO}_2(101)$ surface to be compared with that of the molecular and deprotonated forms.

In the zwitterionic configuration, the proton from the carboxylic group is transferred to the amino group rather than to the surface. Protonation of the amino group ($-\text{NH}_3^+$) prevents its coordination to a surface Ti_{5c} atom, thereby restricting the adsorption to the (0,0) or (0,S) binding modes. A stable zwitterionic structure $\text{ZW-DP}_{\text{SH}}(\text{O},\text{S})$ is obtained when both the carboxylic and thiol groups become deprotonated, with an adsorption energy of -1.81 eV. In this configuration, the proton transferred to the amino group forms one hydrogen bond with a surface O_{2c} site, as shown in **Figure 5a**, whereas the proton dissociated from the $-\text{SH}$ group is transferred to the surface and establishes another hydrogen-bond with one of the non-coordinated carboxylate oxygens.

The bidentate $\text{ZW}(\text{O},\text{O})$ structure, reported by Pantaleone et al. (39) as the most stable configuration based on PBE+D2 calculations, does not correspond to a local minimum within our computational setup (PBE+U+D3; see **Table S1** for details). In fact, during structural optimization, the proton spontaneously transfers to an O_{2c} site, yielding a deprotonated form. In our calculations, the preferred zwitterionic structure is monodentate $\text{ZW}(\text{O})$ with the addition of one hydrogen bond between the transferred proton in $-\text{NH}_3^+$ and a surface O_{2c} site. We identified two different adsorption $\text{ZW}(\text{O})$ configurations with adsorption energies of -1.57 and -1.73 eV (see **Figure S5**), which are less favorable than that (-2.10 eV) of the most stable $\text{DP}_{\text{COOH}}(\text{O},\text{N})$. The larger distance between Ti_{5c} atoms on anatase $\text{TiO}_2(101)$ compared to that on the rutile (110) surface reduces the stability of the bidentate adsorption mode, which could explain why in the zwitterionic form we observe that one carboxylate O-Ti_{5c} bond is broken in favor of the formation of a hydrogen bond between the protonated $-\text{NH}_3^+$ group and a bridging surface O_{2c} site.

An increased stabilization of the zwitterionic form is expected in the presence of water molecules, which may be available in small amounts even under UHV as in our experiments. To explore this possibility, we added one gas phase water molecule in our calculations. Among all our identified hydrated zwitterionic structures (see **Figure S5**), the most stable one is $\text{ZW-DP}_{\text{SH}}(\text{O},\text{S})+1\text{H}_2\text{O}$, also shown in **Figure 5b**. However, this configuration is still less energetically favorable than the hydrated deprotonated $\text{DP}_{\text{COOH}}(\text{O},\text{N})+1\text{H}_2\text{O}$ structure (**Figure 5c,d**), as indicated by their adsorption energies of -2.49 and -2.86 eV, respectively. This result, together with the

Table 1. Vibrational frequencies assignment (in cm^{-1}) corresponding to Figure 4b-d and Figure 5a. Computed values are reported for the three most stable deprotonated configurations and the zwitterionic form. Modes

Assignment	Experiments		Theory				
	Wavenumber	Reference	M(N,S)	DP _{COOH} (O,N)	DP _{COOH} (O,O)	DP _{COOH} (O,S)	ZW-DP _{SH} (O,S)
$\nu_{\text{C=O}}$	1700	(67-69, 73, 74)	1748	-	-	-	-
$\delta_{\text{asym}}\text{NH}_3^+$	1627	(68, 70-74)	-	-	-	-	1614
$\nu_{\text{asym}}\text{COO}^-$	1590	(64-67, 69, 74)	-	1578	1532	1518	1596
δNH_2	1567	(68, 70-74)	1589	1540	1573	1595	-
$\delta_{\text{sym}}\text{NH}_3^+$	1530	(68, 70-74)	-	-	-	-	1504
δCH_2	1457	(73, 74)	1423	1407	1411	1425	1423
$\nu_{\text{sym}}\text{COO}^-$	1406	(64-67, 69, 74)	-	1327	1379	1387	1354

one in anhydrous conditions reported above, and our experimental results provide a rational basis to explain the limited abundance of zwitterionic species observed experimentally.

Spectroscopic Assignment of Adsorption Configurations by DFT calculations: CLS and IR vibrational frequencies

To establish a direct link between the experimentally observed XPS and IR features and specific adsorption geometries, we computed core-level shifts (CLS) and vibrational frequencies for the most relevant configurations. These calculations allow us to assess which adsorption motifs are consistent with the measured spectra and to rationalize differences between molecular, deprotonated, and zwitterionic species. The CLS values for C 1s, N 2s, O 1s, and S 2p are summarized in **Table S2**.

The experimental O 1s spectrum (**Figure 2a**) displays a broad feature at ~ 532 eV, attributed to oxygen atoms bound to carbon. For gas phase cysteine in molecular form, the two carboxylic oxygens are chemically inequivalent with a calculated CLS difference of 2.1 eV (**Table S2**), indicating two well separated components.

Upon adsorption, however, the computed splitting is significantly reduced. In the M(N,S) configuration (**Figure 4a**), hydrogen bonding between the COOH group and a surface O_{2c} site lowers the CLS difference to 1.5 eV, while in the most stable deprotonated structure, DP_{COOH}(O,N) (**Figure 4c**), the calculated splitting decreases to only 0.2 eV. In both cases, the predicted O 1s components fall within the energy range of the experimentally-observed very broad feature (see **Figure 2a**). These results indicate that the experimentally observed broad O 1s peak is fully compatible with both geometries and excludes others that would generate strongly inequivalent oxygen environments.

In the case of the experimental C 1s spectrum (**Figure 2b**), three components corresponding to the inequivalent carbon atoms in cysteine are visible, as discussed above. The peak at the highest binding energy,

289.0 eV, is assigned to the carboxyl carbon, followed by the α -carbon ($\text{C}\alpha$) at 285.9 eV, and the C-S carbon at 285.2 eV. The calculated CLS values (**Table S2**) reproduce this qualitative trend, with the smallest shift for C-S, an intermediate shift for $\text{C}\alpha$, and the largest shift for the carboxyl carbon.

The experimental N 1s spectrum (**Figure 2c**) exhibits two components separated by ~ 2 eV. The peak at 402.2 eV corresponds to protonated amino groups ($-\text{NH}_3^+$), while the peak at 400.3 eV is assigned to neutral $-\text{NH}_2$ groups, either coordinated or non-coordinated to Ti_{5c} . The calculated CLSs (**Table S2**), between the non-zwitterionic configurations and the zwitterionic one (ZW-DP_{SH}(O,S)), show a similar splitting, and the predominance of the $-\text{NH}_2$ signal supports the higher stability of the DP_{COOH}(O,N) configuration over zwitterionic adsorption.

The experimental S 2p spectrum (**Figure 2d**) reveals two sulphur species separated by 2.3 eV. The lower binding energy component at 161.6 eV is assigned to sulphur coordinated to Ti_{5c} sites, whereas the higher binding energy peak at 163.9 eV corresponds to protonated thiol ($-\text{SH}$) species. The calculated CLS difference between Ti-S bonded and $-\text{SH}$ sulphur atoms is approximately 2 eV (**Table S2**), in excellent agreement with experiment. Both the molecular M(N,S) and deprotonated DP_{COOH}(O,N) configurations reproduce this splitting. DFT calculations indicate DP_{COOH}(O,N) as the energetically preferred configuration, in which the sulphur remains protonated (SH) and does not coordinate to the Ti. This is consistent with the experimental S 2p intensity ratio, which indicates a larger contribution from $-\text{SH}$ species compared to Ti-S coordinated sulphur.

To further validate the spectroscopic assignments, vibrational frequencies were computed for the most stable molecular configuration (M(N,S), **Figure 4a**), the three most stable deprotonated configurations (**Figure 4b-d**), and the most stable zwitterionic configuration (ZW-DP_{SH}(O,S), **Figure 5a**). Comparison with the experimental IR data (**Table 1**) shows good agreement

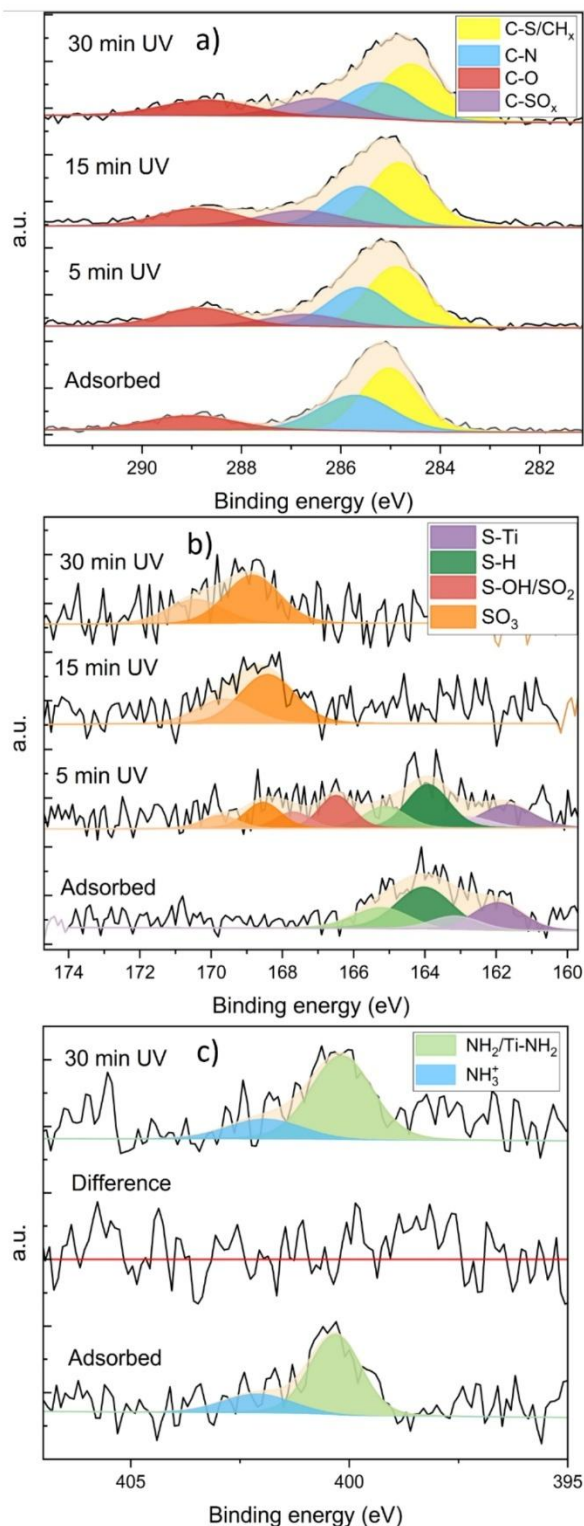


Figure 6. Deconvoluted XP spectra of adsorbed cysteine on anatase $\text{TiO}_2(101)$ under UV irradiation. Experimental data (black) and fitted components (colored) are presented for (a) C 1s, (b) S 2p, and (c) N 1s after 5, 15, and 30 minutes of UV exposure at room temperature and atmospheric pressure. The difference spectrum (30 min – adsorbed) in (c) confirms the absence of changes in nitrogen species.

for both the carboxyl and amino related modes. In particular, the calculated symmetric and asymmetric COO^- stretching frequencies of the deprotonated configurations match the experimentally observed bands, whereas the zwitterionic structure predicts distinct features in the NH_3^+ region that are not dominant in the spectrum. These results further support the predominance of the deprotonated $\text{DP}_{\text{COOH}}(\text{O},\text{N})$ motif. Although hybrid DFT methods generally provide higher accuracy for vibrational analyses, we note that the present calculations were performed using the GGA-PBE functional augmented with D3 dispersion corrections and a Hubbard U term (PBE+U+D3).

Cysteine photooxidation on the anatase $\text{TiO}_2(101)$ surface.

Cysteine Photooxidation by XPS

To elucidate the progression of cysteine photooxidation, stepwise, UV irradiation experiments were performed under atmospheric pressure using exposure times of 5, 15, and 30 minutes in air, corresponding to early, intermediate, and fully oxidized stages, respectively (irradiation details in the S.I). Overall, the XPS data show that photooxidation proceeds selectively at the sulphur moiety, while the carbon and nitrogen regions show no evidence for parallel oxidation. The following section details how this selectivity is reflected across the different core levels.

Figure 6a shows the deconvoluted C 1s spectra acquired before and after UV exposure. Two main spectral changes are observed. First, the component initially assigned to carbon bound to sulphur progressively shifts toward lower binding energy with increasing UV exposure (from 285.2 eV in the pristine state to 284.8 eV after 15 min and 284.6 eV after 30 min). This evolution does not reflect a chemical shift of the C-S bond itself. On the contrary, as sulphur becomes fully oxidized, the intrinsic C-S contribution is expected to decrease. However, this decrease is masked by the simultaneous accumulation of adventitious carbon during UV irradiation under atmospheric conditions. As exposure time increases, hydrocarbon contaminants adsorb on the surface and contribute strongly to the 284.6–284.8 eV binding energy region, progressively dominating this spectral component and shifting its apparent position toward lower binding energies. As a result, the observed peak no longer represents intact cysteine at extended irradiation times but is largely governed by surface carbon contamination, an effect that is well known and is difficult to avoid in ambient pressure photocatalytic experiments (78–82).

The second significant feature is the emergence of a new peak at 286.6 eV, which grows with coverage and falls within the binding energy range of carbon bonded to sulfate or sulfite groups. Instead, the alternative possibility of carbon bonded to nitro species can be ruled out, as **Figure 6b** (N 1s spectrum) shows no evidence of NO_x -related species, which would always appear higher

than 403 eV (83-86). Additionally, the absence of any noticeable change in the N 1s peak suggests that oxidation does not occur at the nitrogen site.

To further verify that oxidation is photon-driven, we performed a control experiment in the dark. A cysteine covered surface was exposed to ambient conditions for 30 min without illumination (**Figure S6**). Under these conditions, no new C-SO_x component appeared in the C 1s region, and no changes were observed in the S 2p spectra, confirming that cysteine oxidation does not occur without photon excitation. On the other hand, the low binding energy growth of the C-S peak was still observed in the dark, consistent with adventitious carbon accumulation rather than chemical transformation.

A pronounced transformation is observed in the S 2p spectrum (**Figure 6b**), where the S-H (163.9 eV) and S-Ti (161.6 eV) peaks disappear with increasing UV exposure, and two new sulphur species emerge at approximately 166.5 eV and 168.7 eV. Oxidation of cysteine at the sulphur site has been reported to involve, depending on the chemical environment, a sequence of sulphur oxyacid species including sulfenic (-SOH) and sulfinic (-SO₂H) acids before reaching the fully oxidized sulfonic form (-SO₃H), also known as cysteic acid (21, 22).

After 5 minutes of exposure, a new peak at 166.5 eV appears, which is consistent with intermediate oxidation states such as sulfenic (-SOH) and sulfinic (-SO₂H) acids and an emerging peak at 168.7 eV. However, at higher UV exposure times (15 and 30 minutes), also the 166.5 eV peak disappears, leaving only the 168.7 eV peak, which is consistent with the fully oxidized sulfonic (-SO₃H) species. The lack of spectral changes between 15 and 30 minutes suggests that the sample reaches complete oxidation within the first 15 minutes of UV exposure.

This behavior is in line with the oxidation pathways proposed for the electrochemical oxidation of cystine in water in a previous study (23). The latter identified both sulfenic (-SOH) and sulfonic acid (-SO₃H) species, reporting approximately 3 eV binding energy separation between them. In contrast, our data show a splitting of 2 eV, suggesting that the peak at 166.5 eV is likely a mixture of sulfenic (-SOH) and sulfinic (-SO₂H) species. Further supporting this peak assignment, studies on sulfonic acid functionalized carbon nanotubes reported an S 2p peak at 169.5 eV, attributed to R-SO₃H species, aligning closely with the peak we observed at 168.7 eV. However, while these comparisons support the proposed peak assignments, the microscopic reaction mechanism and the nature of the reactive intermediates involved under photocatalytic conditions remain to be clarified for the present system.

The O 1s region (**Figure S7**) was also examined before and after 30 min of UV irradiation. No significant changes are observed, as the signal is dominated by lattice oxygen from TiO₂, masking contributions from oxidized adsorbates. Therefore, the oxidation process is primarily

assessed using the more chemically sensitive C 1s and S 2p regions.

Although cysteine oxidation can follow different pathways depending on the environment, the UV experiments presented here show selective transformation of the thiol (-SH) group and a progressive shift of the S 2p signal toward higher binding energy, consistent with stepwise increases in the sulphur oxidation state up to -SO₃H. To rationalize these spectral changes and identify the underlying elementary steps, we combine the experimental XPS observations with DFT calculations of the photooxidation pathway.

Cysteine Photooxidation: DFT calculations

The photooxidation pathway was modeled in the triplet excited state at the HSE06+D3 level using CRYSTAL17, starting from the experimentally observed and energetically favored DP_{COOH}(O,N) adsorption configuration. The relative stability ordering obtained with PBE+U+D3 was confirmed at the HSE06+D3 level of theory (see **Table S1**), further justifying the use of the optimized DP_{COOH}(O,N) as the initial structure (**Figure 4c**). The calculations traced the elementary steps from the adsorbed thiol to the fully oxidized sulfonic acid, enabling direct comparison between computed intermediates and the XPS evolution observed under UV irradiation. **Figure 7** summarizes the proposed mechanism. The reaction is initiated by physisorption of O₂ at a Ti_{5c} site (II), followed by a photoactivated step that forms a chemisorbed superoxo species accompanied by -SH deprotonation and sulphur oxidation (III). This step requires a small electronic energy cost (+0.40 eV), with the photoexcited electron localizing on O₂ (forming O₂⁻) and the hole on the sulphur atom, respectively. As a result, the oxidation state of sulphur increases from -2 to -1, consistent with the initial upward shift of the S 2p binding energy observed experimentally after 5 min UV exposure.

Next, the superoxo intermediate is further reduced by conduction electrons from bulk (reduced) anatase TiO₂, that are readily available due to native oxygen vacancies or other intrinsic defects. This reduction leads to the formation of a peroxo species that is further stabilized by protonation to form an adsorbed hydroperoxo (OOH) on the TiO₂ surface (IV). This highly reactive intermediate drives subsequent sulphur oxidation, either via sequential OH and proton transfer (Va) or through direct O transfer to form -S=O (Vb), the latter being energetically preferred (-2.83 eV). Because of this oxidation, the sulphur oxidation state increases to approximately +1 for -S(·)-OH and +1.5 for -S=O(·). In principle, oxidation states of 0 and +1 would be expected for -S-OH and -S=O, respectively; however, in both cases sulphur is effectively more oxidized to an actual radical species by the photoinduced hole after *hν* irradiation, as evidenced by the presence of an unpaired electron localized on sulphur in -S-OH and partially localized on the sulphur atom of the S=O moiety.

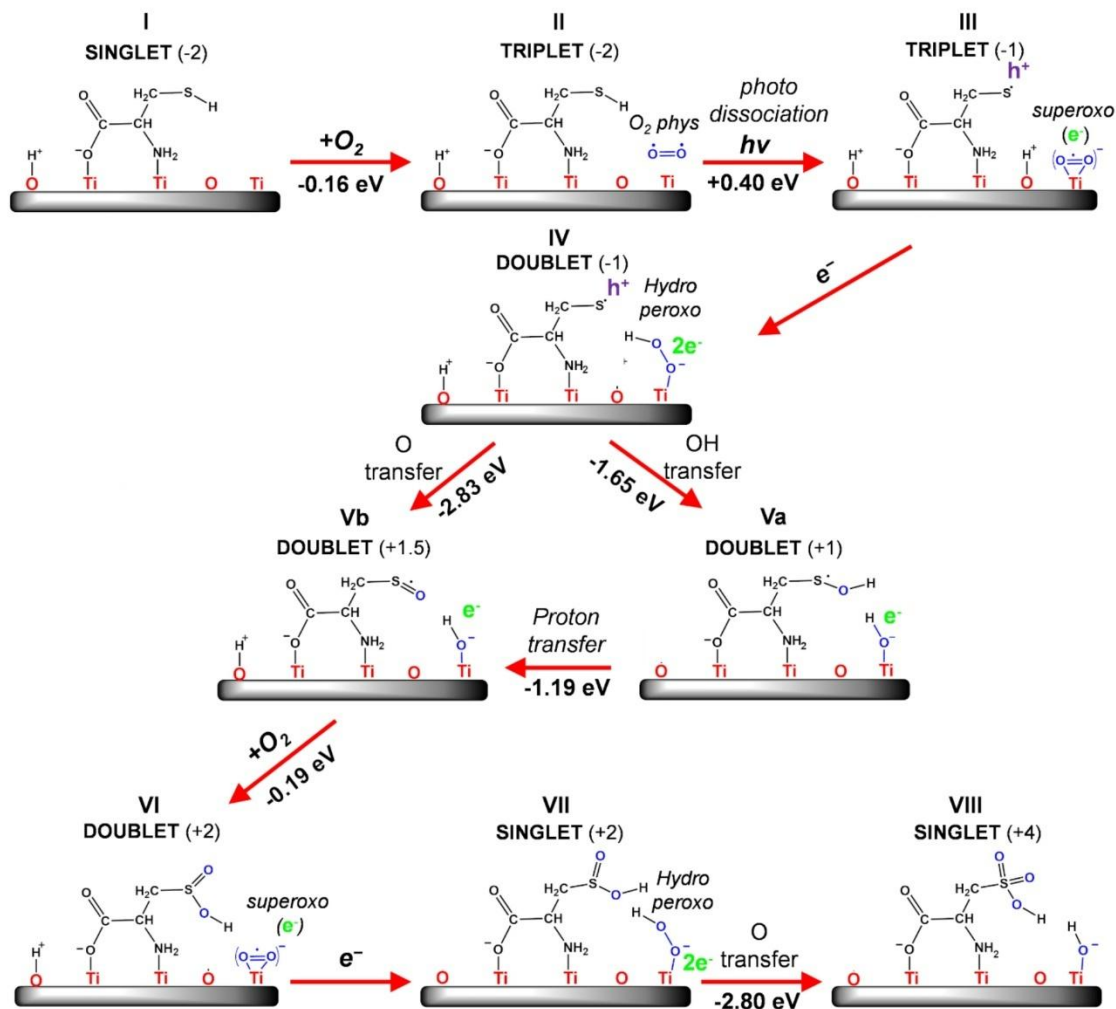
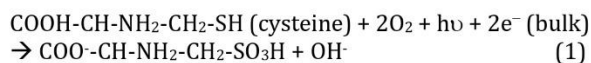


Figure 7: Intermediates of cysteine photooxidation on anatase $\text{TiO}_2(101)$ in the presence of O_2 . For each intermediate, the spin multiplicity of the system is reported, with the oxidation state of sulfur in parentheses. Two reaction steps involve excess electrons transferred from the anatase TiO_2 bulk, which are balanced by surface protons to maintain overall charge neutrality ($e^- + \text{H}^+$) of the periodic model. Oxidation steps are induced by photoexcited holes or hydroperoxide species formed upon transfer of photoexcited electrons and excess bulk electrons to molecular O_2 . The number and localization of photoexcited electrons and conduction electrons from bulk anatase TiO_2 involved in the photooxidation process are shown in green. Unpaired electrons are indicated by dots. Energies are computed with CRYSTAL17 code and the hybrid functional HSE06 with D3 correction.

To complete the oxidation process, a second O_2 molecule is required. This chemisorbs on a Ti_{5c} site while the terminal OH^- at that site is transferred to the $-\text{S}=\text{O}$ group to form a $-\text{SOOH}$ intermediate (overall -0.19 eV), further oxidizing sulphur to an oxidation state of $+2$ (VI). Subsequent reduction of the newly adsorbed O_2 (VII) and oxygen transfer ultimately yield the fully oxidized product, $-\text{SO}_3\text{H}$ (VIII), with a substantial energy gain (-2.80 eV).

The photooxidation mechanism described above requires one photon, two O_2 molecules, and two bulk conduction band electrons to fully oxidize one cysteine $-\text{SH}$ group to a sulfonic acid, while forming a chemisorbed OH^- species. The overall charge and mass balanced reaction can be summarized as:



To connect the computed intermediates with the experimentally observed evolution of the S 2p region under UV irradiation, we evaluated sulphur 2p level shifts along the oxidation pathway, from thiol (formal oxidation state -2) to sulfonic acid ($+4$). The calculations predict a monotonic increase in S 2p binding energy with increasing sulphur oxidation state, in good agreement with the ~ 5 eV shift observed experimentally (Table 2). The only exception is the SOH intermediate; since in the computed energy profile (Figure 7) this intermediate is less favorable than the direct formation of the $-\text{SO}$ species via oxygen transfer, we may conclude that the stepwise oxidation pathway likely bypasses the SOH intermediate.

In the observed trend, the overall variation of CLSs is by 5.5 eV, which is in good agreement with the

experimentally observed increase in the XPS binding energy of ~5 eV.

Finally, the experimental N 1s XPS data indicate that the amino group remains unchanged during UV irradiation. To rationalize this selectivity, we examined a competing pathway in which the -NH₂ group is oxidized to -N-OH following formation of the superoxo/hydroperoxo species (**Figure S8**). This process is energetically less favorable (-1.19 eV) than sulphur oxidation via direct oxygen transfer (-2.83 eV), providing a thermodynamic explanation for the experimentally observed preference for thiol oxidation.

Table 2: For each computed cysteine oxidation intermediate (numbered as in Fig. 7), the formal oxidation state (OS) of S, as determined from the structural formula, the energy position of the S 2p states obtained from the projected density of states, and the corresponding core level shift (CLS), defined as the difference in S 2p energy relative to the -SH reference configuration, are reported.

Intermediate	S group	OS	S 2p (eV)	CLS (eV)
I	-SH	-2	-161.2	0.0
III	-S	-1	-162.3	-1.1
Va	-SOH	+1	-165.0	-3.8
Vb	-SO	+1.5	-164.2	-3.0
VI	-SO ₂ H	+2	-164.4	-3.2
VIII	-SO ₃ H	+4	-166.7	-5.5

CONCLUSIONS

In this work, we combined STM, XPS, FT-IRRAS, and DFT calculations to elucidate the adsorption and photooxidation behavior of cysteine on the anatase TiO₂(101) surface. STM imaging reveals that cysteine adsorbs in a bridging configuration on surface Ti sites, occurring both on terraces and preferentially at step edges. Spectroscopic data indicate that, under UHV conditions, the amino group is predominantly unprotonated on anatase, in contrast to rutile TiO₂(110), and that a significant fraction of molecules interact directly with the surface via the nitrogen and sulphur atoms.

DFT calculations rationalize these observations by identifying two energetically favored and nearly degenerate adsorption configurations: a molecular M(N,S) structure, in which cysteine binds through the amino and thiol groups, and a deprotonated DP_{COOH}(O,N) configuration, where the carboxylate and amino groups coordinate directly to surface Ti sites. The close

energetic competition between these geometries explains the simultaneous presence of molecular and deprotonated species inferred from the experimental data.

Upon UV irradiation in air, cysteine undergoes selective photooxidation at the sulphur site. XPS reveals the disappearance of thiol -SH and S-Ti related components and the emergence of higher binding energy S 2p features consistent with stepwise sulphur oxidation. DFT calculations provide a mechanistic picture of this behavior, showing that photoactivated oxygen species on anatase preferentially oxidize the thiol group through a stepwise pathway involving oxygen transfer reactions, ultimately yielding the fully oxidized sulfonic acid (-SO₃H). The computed energetics account for both the observed sequence of sulphur oxidation states and the absence of competing oxidation at the amino group.

Overall, this study provides a comprehensive experimental and theoretical characterization of cysteine adsorption and sulphur selective photooxidation on anatase TiO₂(101). By combining surface sensitive spectroscopy, microscopy, and DFT calculations, we establish the stable adsorption configurations and elucidate the microscopic pathways governing cysteine photooxidation. These findings advance fundamental insight into amino acid reactivity on TiO₂ surfaces, with implications for photocatalysis and biomolecule-oxide interface chemistry.

ASSOCIATED CONTENT

Crystal preparation methods, cysteine evaporation details, experimental procedures for X-ray photoelectron spectroscopy (XPS), scanning tunneling microscopy (STM), and Fourier-transform infrared reflection absorption spectroscopy (FT-IRRAS); thickness estimation procedure; detailed computational methodology including density functional theory (DFT) calculations, adsorption energy evaluations, and core-level shift calculations; additional figures and tables illustrating surface characterization, calculated binding geometries, adsorption energies, and core-level shifts.

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ABBREVIATIONS

TiO₂, Titanium dioxide; cys, cysteine; XPS, x-ray photoelectron spectroscopy; FT-IRRAS, Fourier-transform infrared reflection absorption spectroscopy; STM; scanning tunneling microscopy; DFT, density functional theory; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; CLS, core-level shift; LEED, low energy electron diffraction; DP, deprotonated; ZW, zwitterionic.

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6: Adsorption and Comparison of Asparagine on TiO₂ Polymorphs

The interaction of polar amino acids with metal oxide surfaces is key in fields ranging from photocatalysis to biointerfaces, yet our molecular level understanding of these systems remains limited. After establishing in previous chapters how cysteine interacts with rutile and anatase TiO₂ surfaces and how its chemistry evolves under illumination, we turn here to L-asparagine, an amino acid whose adsorption behaviour has not yet been experimentally or theoretically resolved on oxide surfaces. Asparagine is structurally distinct from the amino acids considered earlier in this thesis: in addition to the canonical amino and carboxylate groups common to all amino acids, it features a polar carboxamide side chain, capable of participating in hydrogen bonding and surface coordination. This functional group contributes directly to protein structure and molecular recognition (137, 138).

Despite its importance, there is almost no experimental information on this amino acid adsorbed on semiconductor materials. The closest information comes from investigations on metal substrates, where asparagine was shown to adsorb in deprotonated form but without forming ordered structures on Cu(111) (58), and to interact strongly with gold electrodes through both the carboxylate and amide carbonyl groups (59). Complementary theoretical studies on related amino acids, such as glutamine and glutamic acid, suggest that polar side chains have a significant influence on adsorption geometries, with a clear facet dependence predicted between anatase (101) and rutile (110) surfaces (56, 57). These findings indicate that amide containing amino acids may respond differently to their local environment compared with simpler species such as glycine or alanine (42, 139). However, the lack of direct spectroscopic and microscopic data for asparagine on oxide surfaces has left a gap in our knowledge of biomolecule TiO₂ interactions.

The present chapter addresses this gap by providing the first systematic study of L-asparagine adsorption on both rutile $\text{TiO}_2(110)$ and anatase $\text{TiO}_2(101)$ based on STM, XPS, and FT-IRRAS approach. We observed a clear facet dependence in the adsorption behaviour of asparagine. STM images of rutile (110) shows that the molecule preferentially adsorbs in row-confined geometries aligned with the Ti_{5c} rows, consistent with a predominance of bidentate (O,O) carboxylate binding, as expected for many deprotonated carboxylates on this surface. In contrast, anatase $\text{TiO}_2(101)$ displays a substantially higher proportion of diagonally oriented species spanning adjacent Ti_{5c} - O_{2c} rows, a configuration that is consistent with an (O,N) bidentate mode.

XPS enables a quantitative evaluation of these facet-dependent differences. The O 1s spectra on both rutile (110) and anatase (101) surfaces exhibit a single carboxylate component, confirming that adsorption proceeds through dissociative deprotonation rather than molecular COOH binding (18, 57). The N 1s region, however, shows pronounced contrasts: rutile displays a significantly stronger protonated $-\text{NH}_3^+$ component than anatase. This behaviour reflects the dominance of (O,O) geometries on rutile, which leave the α -amino group unbound and available for protonation, whereas on anatase the greater prevalence of (O,N) binding coordinates the nitrogen to a Ti_{5c} site and suppresses its protonation.

FT-IRRAS spectra support this interpretation, showing characteristic carboxylate splitting consistent with bidentate binding on both surfaces and well-defined amide $\nu(\text{C}=\text{O})$ bands whose slight shifts reflect subtle variations in hydrogen bonding between the amide group and surface oxygen of TiO_2 .

Overall, these results provide an atomistic picture of asparagine adsorption on TiO_2 surfaces. They show that the molecule adopts different binding modes on rutile (110) and anatase (101) depending

on carboxylate deprotonation, amine coordination, and amide hydrogen bonding, and that relatively small differences in Ti-Ti spacing and surface geometry lead to measurable changes in protonation state and molecular orientation.

Protonation and Binding Configurations of L-Asparagine on Rutile (110) and Anatase (101) TiO₂ Surfaces

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ABSTRACT: This study presents the first systematic investigation of L-asparagine adsorption on TiO₂ surfaces, using a combining techniques of FT-infrared reflection absorption spectroscopy (FT-IRRAS), scanning tunneling microscopy (STM), and X-ray photoelectron spectroscopy (XPS). We investigated the rutile (110) and anatase (101) surfaces of TiO₂ and reveal that asparagine binds through a deprotonated carboxylate group, with a facet-dependent competition between bridging bidentate (O,O) and (O,N) configuration. STM analysis shows row-confined adsorption on rutile, consistent with the (O,O) configuration, while anatase displays a higher proportion of diagonal binding indicative of (O,N) configurations. XPS data further supports these observations, showing distinct nitrogen and oxygen species, across the two rows on anatase surface after the adsorption of L-asparagine. We also observed that a portion of the adsorbed asparagine undergoes protonation, forming NH₃⁺ species. This protonated state is significantly dominated on rutile (110), whereas anatase (101) predominantly stabilizes the neutral NH₂ configuration. These results underscore the role of surface-dependent acid-base chemistry in governing amino acid asparagine adsorption on TiO₂. The results advance the mechanistic understanding of molecule-oxide interactions and are directly relevant to the design of mixed-phase surface functionalities. These insights also contribute to a broader understanding of fundamental framework for describing biomolecule adsorption on oxide interactions, with implications for catalysis, environmental remediation, and bioengineering applications.

INTRODUCTION

Titanium dioxide (TiO₂) is one of the most studied oxide materials due to its wide range of applications in photocatalysis (1), biomedicine (2), and environmental remediation (3, 4). Its non-toxicity as catalyst, chemical stability, and ability to utilize ultraviolet light make it particularly useful for processes such as water and air purification (5, 6) or anti-pathogen coatings (7-9). TiO₂ crystallizes mainly in two polymorphs, rutile and anatase, whose structural differences have significant implications for surface reactivity, both of which share a tetragonal lattice composed of fivefold coordinated titanium sites, Ti_{5c}, and bridging oxygens (10). The most stable rutile surface is the (110) termination, while the (101) termination dominates the morphology of anatase. Although structurally similar, rutile (110) and anatase (101) differ significantly in surface structure: rutile exhibits shorter Ti-Ti bond and lower step densities, while anatase presents a more open arrangement with higher densities of undercoordinated sites (10-12). These differences strongly influence surface reactivity. Understanding both surfaces is crucial, as commercial photocatalysts such as Degussa P25 consist of mixed anatase and rutile phases, whose synergistic interactions dictate their overall activity (13, 14).

The adsorption of molecules on TiO₂ has been extensively investigated on both rutile (110) and anatase

(101) surfaces. Water (15, 16), carboxylic acids (17, 18), and various organic species (19-21) have been used as model adsorbates to probe surface reactivity. These studies revealed a clear facet dependence: rutile (110) typically favours dissociative adsorption of molecules containing carboxylic groups in bridging bidentate geometries, whereas anatase (101) more often stabilizes molecular or mixed coordination states (17, 22-24). Against this background, amino acids constitute a particularly important class of adsorbates, since they introduce multiple functional groups (carboxyl, amino, and diverse side chains) and are the fundamental building blocks of proteins. Their adsorption is therefore essential for understanding biomolecule-oxide interactions and the mechanisms by which photocatalytic surfaces interact with pathogens and complex biological matter.

Previous work on TiO₂ has largely focused on simple amino acids. Glycine and alanine have served as model systems to investigate conventional carboxylate binding (25, 26), while cysteine has garnered interest because of its thiol-containing side chain (27, 28). Our recent investigation of cysteine adsorption on rutile (110) revealed that, contrary to the prevailing assumption that amino acids bind primarily in deprotonated (O,O) carboxylate geometries, cysteine can also adopt (O,N) and (O,S) bridging configurations, indicating a more

intricate adsorption process than previously recognized (29). This highlights the complexity of side chain functional groups and the need to extend adsorption studies beyond simple amino acids.

Among the 20 proteinogenic amino acids, asparagine (Asn) is particularly relevant due to its polar, uncharged carboxamide side chain, which plays a key role in hydrogen bonding and ligand recognition in proteins (30, 31). Despite its significance, no experimental studies have yet examined asparagine adsorption on photocatalytic oxide surfaces, the closest information available comes from studies on metallic substrate. STM experiments on Cu(111) revealed that asparagine adsorbs in a deprotonated form but does not form ordered superstructures, in contrast to nonpolar amino acids such as leucine and glycine (32). Electrochemical studies on gold electrodes showed strong adsorption through the deprotonated carboxylate and the amide carbonyl group, demonstrating the active role of the side chain in adsorption (33). Studies on structurally similar amino acids also provide useful insight. Computational work by Pantaleone et al. showed that for glutamic acid and glutamine, close analogues of asparagine, the most stable adsorption geometry is facet dependent: on anatase (101), deprotonated (O,N) binding is favoured, whereas on rutile (110) the preferred mode is bidentate (O,O) coordination (34, 35). Experimentally, XPS and NEXAFS studies of glutamic acid on rutile (110) confirmed carboxylate anchoring with a coexistence of deprotonated and zwitterionic species (36). These observations provide a baseline for polar amino acids, yet the adsorption of asparagine on oxide surfaces remain unaddressed.

In this work, we address this gap by presenting the first combined STM, XPS and FT-IRRAS investigation of L-asparagine adsorption on rutile (110) and anatase (101) surfaces. By directly comparing the two TiO₂ polymorphs, we elucidate the role of the side chain in binding, deprotonation, and molecular orientation. Furthermore, this study provides for the first time, XPS and FT-IRRAS results of asparagine adsorption on oxide surface in addition to STM images.

EXPERIMENTAL PROCEDURE

Single crystalline rutile TiO₂(110) and anatase TiO₂(101) samples (8 mm × 8 mm × 2 mm, Surface Net Ltd.) were cleaned by repeated cycles of Ar⁺ sputtering (1 keV, 10⁻⁶ mbar Ar⁺, 5 min) and annealing. For rutile, the annealing sequence consisted of 10 min at 1000 K in 10⁻⁶ mbar O₂ followed by 10 min under UHV at the same temperature, which yielded flat and uncontaminated surfaces with minimal Ti³⁺ states, in agreement with previous reports on well-prepared rutile (110) (11). For anatase, annealing was performed for 10 min at 700 K in 10⁻⁶ mbar O₂ and subsequently for 10 min at 950 K under UHV, resulting in a clean and stoichiometric anatase (101) surface, as reported in earlier studies (37). Surface order and cleanliness in both cases were confirmed by sharp (1×1) LEED patterns and XPS, which revealed the

absence of C 1s and O 1s contaminants and, in the case of rutile, only a minimal Ti³⁺ component (Figure S1).

Asparagine deposition was performed under ultra-high vacuum (UHV) conditions following the procedure established for other amino acids (38, 39). For XPS and STM experiments, evaporation was carried out in a load lock connected to the STM chamber with a base pressure in the low 10⁻⁹ mbar range. Following exposure, the samples were transferred through a UHV tunnel with a base pressure of low 10⁻¹⁰ mbar range, with the entire transfer requiring approximately 15 min. The gas line containing the amino acid was thoroughly pumped, baked, and heated to 130 °C during exposure. The temperature was monitored using a type K thermocouple attached to the glass tube containing the asparagine powder.

All the experiments were carried out at the DESY Nanolab at the Centre for X-ray and Nano Science, DESY, Hamburg (40). The XPS instrument is equipped with a monochromated Al K α source (1.486 keV) and a Phoibos 150 hemispherical energy analyser, operating under a base pressure of the low 10⁻¹⁰ mbar. Data analysis was performed using CasaXPS software.

STM images were acquired using a combined STM/AFM (atomic force microscopy) system (XA form Omicron) operating under UHV conditions at a pressure of the low 10⁻¹¹ mbar range. Measurements were conducted in constant current mode at room temperature, employing a tungsten tip. Scanning parameters included voltage ranges from 1.4 V to 1.8 V for rutile (110) and 1.0 to 1.3 V for anatase (101), and current ranges from 0.1 nA to 0.3 nA.

FT-IRRAS was performed using a spectrometer (Bruker Vertex V80) connected to a UHV chamber with a base pressure of the low 10⁻¹⁰ mbar. Each IR spectrum was taken in reflection mode with 512 scans at a resolution of 2 cm⁻¹.

RESULTS AND DISCUSSION

Before interpreting our STM results of asparagine on TiO₂, we first review the morphology of the two most widely studied TiO₂ surfaces. The rutile (110) surface consists of parallel rows of fivefold coordinated titanium atoms (Ti_{5c}) extending along the [001] direction, separated by rows containing bridging oxygen atoms (O_{br}) (10). In STM, the Ti_{5c} rows appear as bright linear features, whereas the O_{br} rows are resolved as darker depressions due to their lower electronic density of states (41, 42). By contrast, the anatase (101) surface displays a more corrugated topography. STM investigations have shown that the bright protrusions arise from Ti_{5c}-O_{2c} pairs, with both species contributing to the tunneling contrast (43, 44). The anatase (101) surface forms a sawtooth structure, composed of Ti_{5c} and twofold-coordinated oxygen (O_{2c}) atoms along the [010] direction, with Ti_{6c} and O_{3c} atoms appearing as darker regions in STM images (10). Crystallographic assignment in STM images can be achieved by analyzing

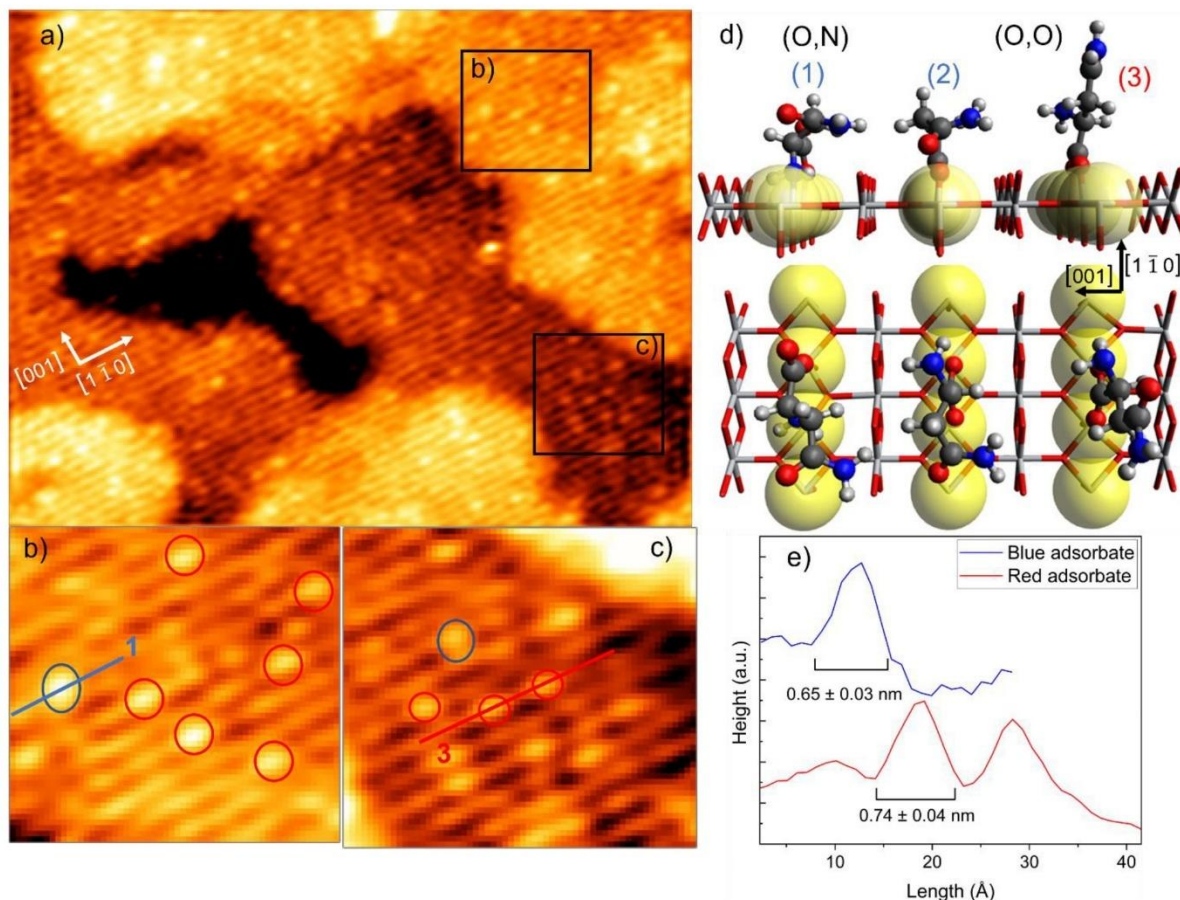


Figure 1. (a) STM images of L-asparagine adsorption on rutile (110) after exposure to 1 L of asparagine at room temperature. The 35 x 22 nm image is taken with 1.7 V of bias voltage and 0.3 nA current. (b) and (c) magnification from (a). (d) Schematic representation of the molecular binding modes, with Ti_{5c} rows highlighted in yellow representing the STM contrast. Gray, red, blue and white spheres represent C, O, N and H, respectively while red and white sticks represent O and Ti atoms of the surface.

island shapes and step edges, allowing the assignment of the $[10\bar{1}]$ direction (12). Additionally, line profiles along $[010]$ yield a periodicity of 0.37 nm, consistent with the expected Ti-Ti spacing in **Figure S2** (16, 17).

On rutile (110), previous results on carboxylic acids show that they typically adsorb on top of Ti_{5c} rows in a bidentate (O,O) configuration (42, 45, 46). For amino acids, Qiu and Barteau (25) demonstrated that glycine forms ordered (2×1) overlayers aligned along the Ti rows, consistent with dissociative adsorption of the carboxyl group. Similarly, our previous work on cysteine demonstrated adsorption on Ti_{5c} rows, with molecules adopting (O,O), (O,S), or (O,N) bridging configurations. A comparable behavior can be expected for asparagine which likely will adsorb also on top of this Ti_{5c} rows.

Figure 1a presents a STM image of rutile (110) surface after exposure to 1 L of asparagine. Two distinct adsorbates are observed (**Figures 1b,c**). Red species are positioned directly on top of the bright Ti_{5c} rows, with their density localized within a single row and an average lateral size of 0.74 ± 0.04 nm. In contrast, species marked in blue also sit on the Ti_{5c} rows but appear slightly indented, with their apparent electronic density extending toward the adjacent O_{br} row. Their measured

apparent size is slightly smaller at 0.65 ± 0.03 nm. Line profiles are provided in **Figure 1e**.

The schematic in **Figure 1d** provides a qualitative structural interpretation (yellow shading highlights the Ti_{5c} rows). The models were constructed using Avogadro with a universal force field, and are intended as illustrative rather than DFT-optimized geometries (47). The red species are consistent with molecules centered on a Ti_{5c} row in an upright geometry, most naturally assigned to an (O,O) carboxylate configuration (model 3). In contrast, the blue species, slightly smaller are tilted configurations extending slightly across the row. This appearance can arise from either (i) an (O,N) bidentate configuration (model 1), where the carboxylate O and the backbone amine N bind to a Ti_{5c} row while the side chain amide points toward the O_{br} row, or (ii) an (O,O) configuration (model 2) in which the side chain amide also leans toward the O_{br} row. In both scenarios, the smaller apparent size and off row contrast of the blue species are consistent with a redistribution of electronic density toward the bridging oxygen trough, likely facilitated $N-H\cdots O$ hydrogen bond interactions between the amide group and neighboring O_{br} atoms.

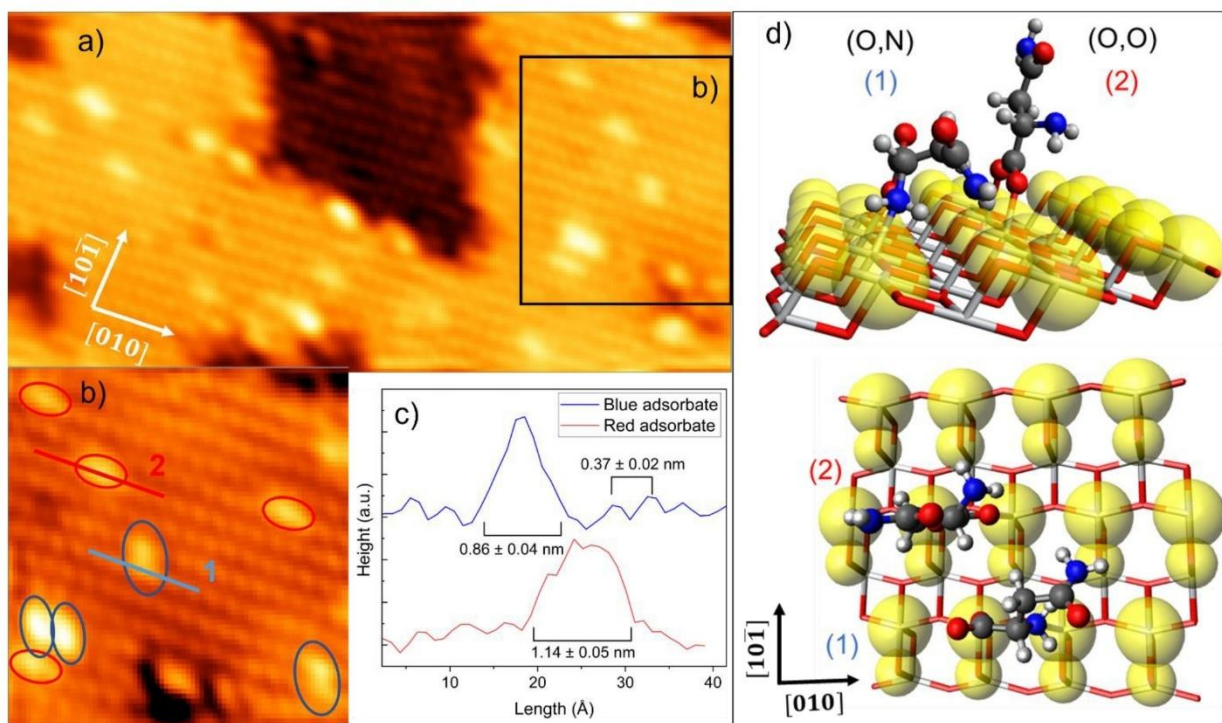


Figure 2. (a) STM images of L-asparagine adsorption on rutile (110) after exposure to 1 L of asparagine at room temperature. 25 x 10 nm; image taken with 1.1 V of bias voltage and 0.3 nA current. (b) magnification. (c) Schematic representation of the molecular binding modes, with Ti_{5c} rows highlighted in yellow representing the STM contrast. Gray, red, blue and white spheres represent C, O, N and H, respectively while red and white sticks represent O and Ti atoms of the surface.

In our recent study of cysteine adsorption on rutile (110), DFT calculations indicated the (O,N) bidentate configuration to be lower in energy than (O,O), while independent spectroscopic evidence established that both configurations are present on the surface, underscoring that amino acid adsorption on rutile (110) surface is not restricted to a single binding geometry. Our interpretation is consistent with the computational study of Pantaleone et al., who predicted that for glutamine, a close structural analogue of asparagine, the (O,O) geometry represents the most stable configuration on rutile (110) [35].

Turning to anatase (101) direct experimental evidence for amino acid adsorption on anatase is limited. One relevant example is p-aminobenzoic acid (pABA) on anatase (101), where XPS and NEXAFS confirmed bidentate (O,O) anchoring of the carboxylate group, with the amino substituent modulating molecular orientation [48]. Carboxylic acids have been more systematically studied: formic acid exhibits both monodentate and (O,O) bidentate species depending on adsorption temperature and coverage [24, 49]. While acetic acid predominantly forms (O,O) bidentate acetate at room temperature [17, 50]. Ma et al. [22] further demonstrated via STM that interconversion between bidentate and monodentate geometries can be mediated by surface hydroxyls. Overall, unlike rutile (110), anatase (101) does not strongly stabilize the (O,O) bidentate configuration for carboxylic acid, as the larger

Ti_{5c} - Ti_{5c} spacing renders monodentate adsorption nearly competitive.

Figure 2a shows an STM image of anatase (101) after exposure to 1 L of asparagine. The bright protrusions correspond to Ti_{5c} - O_{2c} pairs. Two types of adsorbates can be distinguished in **Figure 2b**. Red species are aligned along the [010] direction, centered on Ti_{5c} - O_{2c} pairs, with their apparent density largely confined to a single row. Their lateral extension corresponds to approximately three bright protrusions, indicating that they are centered over three Ti_{5c} atoms, with an average size of 1.14 ± 0.05 nm. In contrast, blue area shows species sit diagonally across neighboring rows, producing a band indented contrast along $[10\bar{1}]$ direction. Their apparent size is smaller, close to the spacing of two Ti_{5c} atoms, with an average of 0.86 ± 0.04 nm. Line profiles supporting these measurements are provided in **Figure 2c**.

The schematic representations in **Figure 2d** provide qualitative structural assignments. As for rutile, the models were generated with Avogadro [47]. The blue species, being smaller, are most consistent with an (O,N) bidentate configuration (model 1), in which the carboxylate oxygen binds to one Ti_{5c} site while the backbone amine coordinates to a neighboring Ti_{5c} site along the [010]. This geometry naturally orients the side chain amide toward the O_{2c} row, allowing N-H...O interactions. By contrast, the red species, which are larger at 1.14 ± 0.05 nm (around three Ti_{5c} spacings),

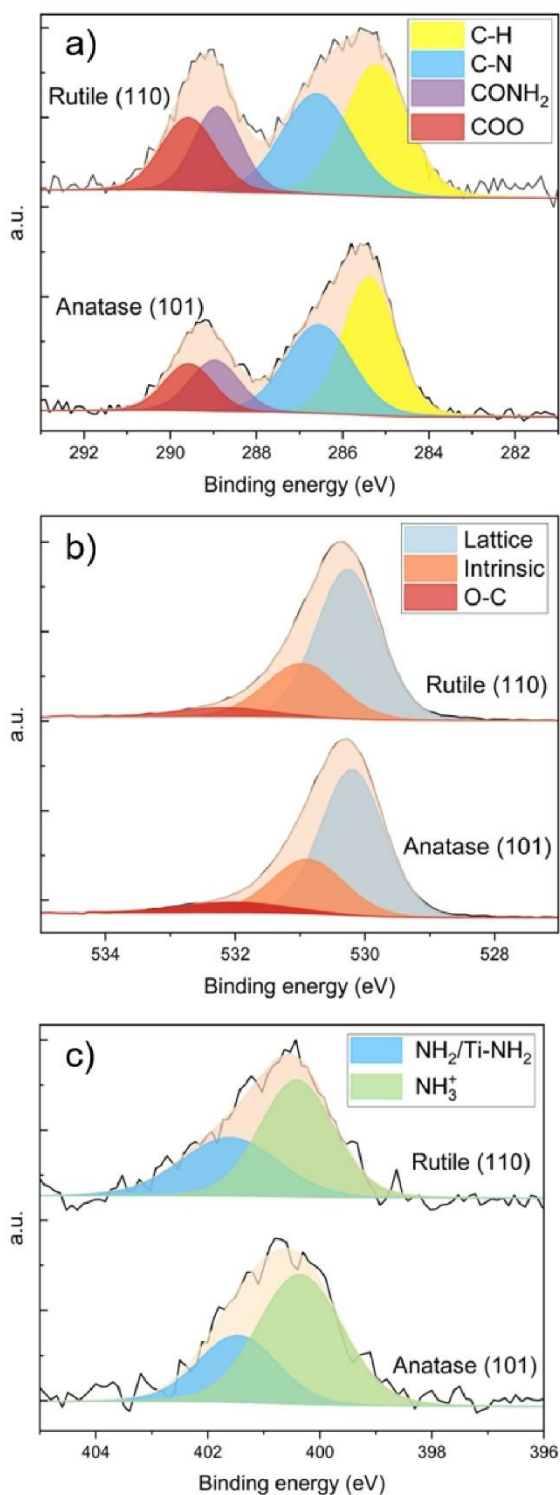


Figure 3. Experimental (black lines) and deconvoluted XPS spectra (colored areas) of L-asparagine on TiO_2 surfaces (a) C 1s, (b) O 1s, (c) N 1s core levels.

correspond to molecules aligned along [010] and centered on a single row, consistent with an (O,O) bidentate carboxylate geometry (model 2). The difference in apparent size between red and blue species

therefore supports their structural assignment, with red (O,O) configurations appearing more extended along the row and blue (O,N) species spanning diagonally across two rows.

The relative proportion of red and blue species is notably closer on anatase than on rutile, where (O,O) binding clearly dominates. This difference can be traced to the larger $\text{Ti}_{5c}\text{-Ti}_{5c}$ separation on anatase (101), which weakens the energetic preference for bridging (O,O) adsorption and brings alternative configurations into competition. Consistent with these findings, computational studies by Pantaleone et al. highlight that the larger Ti-Ti distance in anatase reduces the stability gap between (O,O) and (O,N) geometries, making the latter competitive for amino acids with side chain donor groups (34, 35). Taken together, our STM data confirm a consistent trend across both TiO_2 polymorphs. On rutile (110), asparagine predominantly adopts an (O,O) bidentate configuration, reflecting the excellent match between the carboxylate O-O distance and the Ti-Ti separation. In contrast, on anatase (101) the larger Ti-Ti spacing reduces the stabilization of (O,O), allowing (O,N) binding geometry to compete.

To clarify the adsorption mode and obtain more information about the chemical state of asparagine, we complemented our measurements with XPS and FT-IRRAS.

XPS spectra were collected on rutile (110) and anatase (101) surfaces after asparagine adsorption. Prior to deposition, the clean surfaces showed no detectable carbon contamination, hydroxyl, and adsorbed water; representative C 1s and O 1s spectra and LEED patterns are provided in **Figure S.1**. After exposure, the deconvoluted C 1s spectrum revealed four components, consistent with the four chemically distinct carbon atoms in asparagine (**Figure 3a**). The peak at 289.5 eV is assigned to the carboxylate carbon (-COO-), the one at 288.6 eV to the side chain amide (-CONH₂), the 286.5 eV feature to the α -carbon bonded to the amino group, and the peak at 285.2 eV to the methylene β -carbon (-CH₂). The same sequence is observed for both TiO_2 polymorphs, with only minor shifts (± 0.1 eV) between rutile and anatase. No C 1s reference spectra for asparagine have been reported to date. However, related systems provide suitable comparison. Artemenko et al. (51) reported C 1s data for glutamine, a structurally similar amino acid with identical functional groups but a longer side chain, showing aliphatic carbons at 285.0 eV, a C-N component near 286.1 eV, and carboxylate/amide carbons at 288-289 eV. Other studies demonstrated that -COO consistently appear at higher binding energy than amidic species in C 1s region, with amide signals typically between 287.9-288.3 eV and carboxylates between 289.3-290.5 eV (52, 53).

A clear difference between rutile (110) and anatase (101) lies in the relative intensities of the C 1s components. Whereas rutile exhibits an approximately 1:1:1:1 ratio consistent with the four carbons of asparagine, the anatase spectrum is shifted toward the

lower binding energies (aliphatic and α -C), showing comparatively weaker carboxylate and amide signals.

At first glance, this variation could arise from extrinsic or surface related factors. The presence of additional aliphatic carbon contamination on anatase would enhance the low energy region. However, both surfaces were verified to be carbon free prior to dosing, and the deposition procedure employed was identical making this explanation unlikely. Photon beam induced decomposition could also reduce the carboxylate signal through CO or CO₂ desorption, yet no time dependent changes in the C 1s or O 1s peak ratios were detected under X-ray illumination, ruling out beam damage as the main cause. Similar behavior, in which the aliphatic contribution dominates and the carboxylate peak is attenuated, has been reported for other amino acids, including aspartic acid on Ni(100) (54), serine on Cu(110) (55) and alanine on Ni(111) (56) as well as for *p*-aminobenzoic acid on TiO₂ (48). In all these systems, the effect was attributed to photoelectron diffraction phenomena and is therefore assigned here as the origin of the differences observed between the two TiO₂ polymorphs.

Figure 3b shows the deconvoluted O 1s spectra before and after asparagine adsorption on TiO₂ surfaces. The clean rutile (110) and anatase (101) samples exhibit two intrinsic components: a main lattice oxygen peak at 530.3 eV and a secondary feature at 531.1 eV, commonly attributed either to intrinsic asymmetry in the oxide line shape or to surface species such as hydroxyls or, alternatively, oxygen atoms close to vacancy sites (57). Upon asparagine adsorption, both polymorphs display a new component at 532.0 $\pm$ 0.1 eV, assigned to oxygen atoms in the carboxylate group. The absence of any additional high binding energy feature above 533 eV indicates that the carboxyl group becomes deprotonated upon adsorption. A protonated COOH would yield two distinct O 1s peaks separated by 1-1.3 eV, with the OH oxygen shifted to higher binding energy, yet only a single carboxylate feature is observed, confirming dissociative adsorption (18, 58). Comparable binding energies have been repeatedly reported for COO⁻ species in amino acids and related carboxylates on TiO₂ and other oxides (38, 59-61) further supporting this interpretation. However, XPS alone cannot unambiguously distinguish whether the observed COO⁻ component originates from a purely (O,O) bridging bidentate configuration or from a mixed (O,N) adsorption configuration. In both geometries, the carboxyl group is deprotonated and gives rise to a single carboxylate signal in the O 1s region, with energy differences $\leq$ 0.1 eV.

Figure 3c shows the N 1s spectra of asparagine adsorbed on rutile (110) and anatase (101), both displaying two well defined components separated by approximately 1.2-1.5 eV. On anatase, the lower binding energy peak appears at 400.3 eV, while the higher one is found at 401.5 eV, on rutile the corresponding values are 400.4 eV and 401.7 eV, respectively. These energies and their splitting are consistent with previous reports of

amino acids and related molecules adsorbed on oxide and metal surfaces (62-66). The main component around 400.3-400.4 eV originates from several overlapping species. It primarily corresponds to the neutral amino group (-NH₂) bonded to the α -carbon, but may additionally include contributions from nitrogen atoms coordinated to surface titanium (H₂N-Ti), which are expected to appear in the same binding energy range. This situation closely resembles that observed for cysteine on TiO₂ surfaces, where both weakly and strongly interacting NH₂ species were grouped under a single assignment owing to their minimal core level separation (29). In addition, asparagine contains a side chain amide (-CONH₂) group whose nitrogen also appears between 400.0 and 400.8 eV (52, 53). These contributions, α C-NH₂, surface bound NH₂ and amide nitrogen, cannot be resolved individually, since they overlap within the same binding energy region.

The second (blue) component at 401.5-401.7 eV corresponds to protonated amino species (-NH₃⁺). This assignment is consistent with systematic studies of aliphatic and aromatic amines, where protonated nitrogen appears at higher binding energy than neutral nitrogen (61-65). The presence of this component indicates that a fraction of the adsorbed asparagine is protonated, adopting an (O,O) adsorption geometry in which the amino group does not interact with the surface and is therefore free to accept a proton.

A distinct difference between the two TiO₂ polymorphs lies in the relative intensities of these nitrogen components. On rutile (110), the 401.7 eV -NH₃⁺ peak is significantly stronger than on anatase (101). Since both samples were prepared and analysed under identical conditions, this variation cannot be attributed to surface contamination or molecular coverage of asparagine but rather reflects inherent differences in adsorption geometries. DFT calculations (34, 35), together with our STM analysis, indicate that the larger Ti-Ti separation on anatase stabilizes the (O,N) bridging bidentate adsorption mode, in which the amino group remains deprotonated, whereas rutile (110) preferentially stabilizes (O,O) geometry that leaves the -NH₂ group unbound and therefore it can accept a proton. Moreover, rutile surfaces are known to exhibit a higher tendency toward hydroxylation and water dissociation, which can further promote the formation of zwitterionic species by stabilizing the protonated amino group through hydrogen bonding with surface hydroxyls (67). These results align with STM observations, which show a higher proportion of (O,N) species (blue) on anatase, whereas on rutile, nearly all adsorbed molecules adopt the (O,O) configuration.

To gain additional insight into the adsorption behavior of L-asparagine on TiO₂ surfaces, we measured FT-IRRAS of asparagine adsorbed on both anatase (101) and rutile (110) surfaces (**Fig. 4a, b**). Although direct studies of asparagine adsorption on metal-oxide surfaces are limited, we compare our assignments here against solid state spectra (68), water solution data, and IRAS

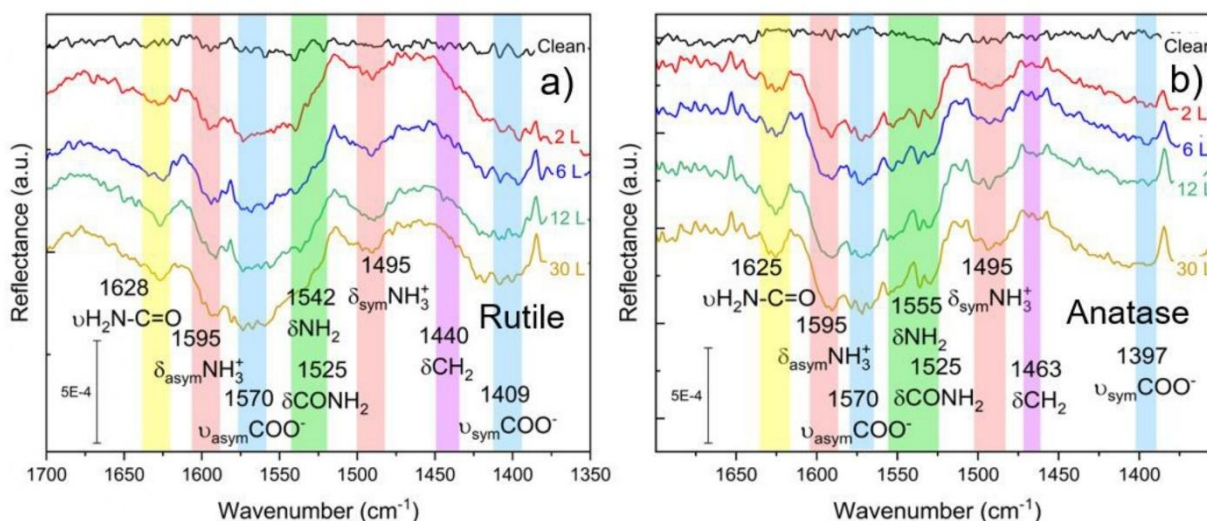


Figure 4. FT-IRRAS spectra for different coverage of asparagine on TiO₂ surfaces at room temperature (a) Rutile (110) and (b) Anatase (101).

measurements on gold electrodes (33). The first observable band at 1625-1628 cm⁻¹ is assigned to the stretching of the amide C=O bond ($\nu_{C=O}$). In asparagine powder pressed into a pellet with KBr, Casado et al. (68) report the amide C=O band around 1656 cm⁻¹, while Słojkowska et al. (33), who studied both solid and solution forms of asparagine, report the amide $\nu_{C=O}$ at 1645 cm⁻¹. Upon adsorption to a gold electrode, the band shifts downward to 1616 cm⁻¹, likely due to hydrogen bonding with the surface. This downward shift is consistent with previous studies, which suggest that hydrogen bonding weakens and lengthens the C=O bond, thereby lowering the wavenumber of the vibration (69–71). According to Larkin's book for IR organic assignment, primary amines typically exhibit strong IR bands in the 1610-1660 cm⁻¹ range (72). A study on benzamide adsorption on TiO₂ reports the amide C=O stretching at 1654 cm⁻¹ (73). The band at 1625-1630 cm⁻¹ in our work aligns with the behavior of a primary amide group interacting via hydrogen bonding particularly with the nearby O_{2c} atoms on rutile (110) and anatase (101).

Moving to lower wavenumbers, in line with XPS data indicating surface NH₃⁺ species, we observe both asymmetric and symmetric deformations of NH₃⁺ at around 1595 cm⁻¹ and 1495 cm⁻¹ respectively. On Au, Słojkowska et al. found the asymmetric deformation $\delta_{asym}NH_3^+$ at around 1590-1615 cm⁻¹, while the symmetric deformation $\delta_{sym}NH_3^+$ appears near 1494 cm⁻¹. Ustunol et al. reported similar behavior for four different amino acids adsorbed on TiO₂ nanoparticles and in water solution, with the $\delta_{asym}NH_3^+$ overlapping with COO⁻ stretching modes, and the peak positions falling within the same range as our observations (74). These findings corroborate with previous studies done on the adsorption of amino acids on TiO₂ in water media (75–77).

For the carboxylate group, we observe the asymmetric stretch $\nu_{asym}COO^-$ at 1570 cm⁻¹ and the symmetric $\nu_{sym}COO^-$ at 1397 cm⁻¹ for anatase (101) and at 1409 cm⁻¹ for rutile (110). The sharp, upward pointing band at 1385 cm⁻¹ is a reproducible interferometer absorption artifact unrelated to asparagine adsorption, also observed in our previous cysteine adsorption study on rutile. The assignment of these bands is consistent with asparagine in solution and on gold electrodes, where $\nu_{asym}COO^-$ is reported around 1581-1591 cm⁻¹ and the $\nu_{sym}COO^-$ around 1400-1410 cm⁻¹ (33). Paszti and Gucci (78) describe band positions and splitting for different COO configurations of amino acids adsorbed on TiO₂. In monodentate configurations, $\nu_{asym}(O=C-O-Ti)$ is always above 1600 cm⁻¹, similar to carbonyl stretching. For bridging bidentate adsorption (O,O), the separation between $\nu_{asym}COO^-$ and $\nu_{sym}COO^-$ is around 200 cm⁻¹, comparable to what we observe. Overall, the position of the IR bands and their splitting in our spectra indicate a bridging bidentate configuration.

Finally, the bands around 1555-1525 cm⁻¹ correspond to the deformations of the neutral amino group (δ_{NH_2}) and the NH₂ deformation in the amide. This assignment agreed with previous reports for amino acids in aqueous media and standard references (Handbook of Amines; Larkin) (72, 74, 79). Ustunol et al. observed similar deformations for lysine (1558 cm⁻¹) and glutamic acid (1551 cm⁻¹), while amide NH₂ deformations generally appear at slightly lower wavenumbers than free amines, in consistent with our observations.

In both cases, the FT-IRRAS spectra of L-asparagine adsorbed on anatase and rutile are very similar, indicating that the adsorption modes of asparagine on both polymorphs are largely the same. The dominant adsorption mode in both polymorphs is (O,O), as established by STM and XPS, though anatase exhibits a higher proportion of (O,N) interactions compared to rutile. This subtle difference in surface environment

likely accounts for the observed shift in the $\nu_{\text{sym}}\text{COO}^-$ band, appearing at 1397 cm^{-1} for anatase and 1409 cm^{-1} for rutile. The presence of more (O,N) species in anatase, as seen in STM, is consistent with the FT-IRRAS results, providing further support for the correlation between surface structure and adsorption behavior.

CONCLUSIONS

This work provides the first systematic understanding of L-asparagine adsorption on TiO_2 by combining STM, XPS, and FT-IRRAS on the prototypical rutile (110) and anatase (101) terminations. Across both facets, asparagine binds through a deprotonated carboxylate, with a facet dependent competition between bidentate (O,O) and (O,N) geometries.

STM resolves two geometries on each surface. On rutile (110), row confined protrusions dominate and are consistent with (O,O) carboxylate bridging aligned along Ti_{5c} rows. On anatase (101), a larger fraction of diagonally oriented features appears, consistent with (O,N) binding mode that bridges across rows and engages the side chain amide in Hydrogen-bonding. XPS independently supports this assignment. O 1s shows a single carboxylate component characteristic of dissociative adsorption on both facets. In N 1s, rutile displays a comparatively stronger $-\text{NH}_3^+$ contribution, consistent with (O,O) geometries that leave the backbone amine unbound and available for protonation, whereas anatase exhibits relatively enhanced neutral NH_2 intensity, in line with (O,N) configurations that coordinate the amine and disfavour protonation.

These results are relevant on several fronts. First, they rationalize the well-known performance of mixed-phase photocatalysts (e.g., P25): a heterogeneous distribution of binding motifs across facets provides multiple, complementary adsorption pathways and protonation states that can facilitate charge transfer and interfacial chemistry. Second, they deliver the first atomistic picture of asparagine on TiO_2 , establishing a benchmark dataset based on STM fingerprints, and XPS core level assignments. Finally, they provide transferable rules for polar, amide-bearing residues at oxide interfaces, rules that can inform molecular models of peptide and protein adhesion and guide surface-functionalization strategies for catalysis, environmental remediation, and biointerfaces.

ASSOCIATED CONTENT

Clean surface characterization LEED and XP spectra; XPS peak fitting protocol.

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ABBREVIATIONS

TiO_2 , Titanium dioxide; cys, cysteine; XPS, x-ray photoelectron spectroscopy; FT-IRRAS, Fourier-transform infrared reflection absorption spectroscopy; STM; scanning tunneling microscopy; DFT, density functional theory; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; CLS, core-level shift; LEED, low energy electron diffraction; DP, deprotonated; ZW, zwitterionic.

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7: Summary and Future Work

This thesis investigated the molecular-level interaction of biologically relevant amino acids with well-defined TiO_2 surfaces, with particular emphasis on adsorption mechanisms and photocatalytically driven chemical transformations. Using single crystalline rutile $\text{TiO}_2(110)$ and anatase $\text{TiO}_2(101)$ as model systems, this work aimed to establish how individual functional groups in amino acids interact with TiO_2 surfaces and how these interactions influence surface reactivity under illumination. The study was motivated by the broader context of photocatalytic disinfection and environmental remediation, where TiO_2 surfaces are known to inactivate microorganisms and degrade biomolecules, while the microscopic mechanisms governing these processes remain insufficiently understood.

A surface science approach was adopted in order to isolate and analyze these interactions with atomic and molecular precision. UHV preparation of well-defined oxide surfaces, combined with scanning tunnelling microscopy (STM), X-ray photoelectron spectroscopy (XPS), and Fourier-transform infrared reflection-absorption spectroscopy (FT-IRRAS), allowed the adsorption geometries, bonding configurations, and chemical transformations of amino acids to be resolved. Density functional theory (DFT) calculations provided complementary insight into the stability and electronic structure of the observed adsorption configurations. Within this framework, two amino acids with chemically distinct side chains were investigated, L-cysteine and L-asparagine.

The adsorption of L-cysteine on rutile $\text{TiO}_2(110)$ revealed a significantly more complex bonding behaviour than previously assumed. Rather than forming a single well-defined adsorption geometry, cysteine was found to adopt multiple configurations that coexist on the surface. The carboxylate group plays a central role in anchoring the molecule to the oxide through the

DP(O,O)/ZW(O,O) configuration, which is consistent with adsorption motifs commonly observed for carboxylic acids on TiO₂. In addition to this geometry, mixed coordination modes involving other functional groups were identified, in particular DP(O,N) and DP(O,S). The latter demonstrates that sulfur can coordinate directly to Ti surface sites without cleavage of the C-S bond, showing that the thiol group participates directly in surface bonding. STM measurements further revealed that adsorption occurs preferentially along the Ti_{5c} rows of the rutile surface and that intermolecular interactions lead to the formation of dimeric structures even at low coverage. Spectroscopic data confirmed the coexistence of multiple protonation states, reflecting the complex acid-base chemistry that arises when multifunctional molecules interact with oxide surfaces (20).

For L-cysteine on anatase TiO₂(101), the adsorption picture is distinctly different (Chapter 5). The combined experimental and theoretical results show that cysteine on anatase does not predominantly adopt the same DP(O,O)/ZW(O,O) motif as on rutile. Instead, anatase TiO₂(101) stabilizes mainly mixed coordination geometries, in particular DP_{COOH}(O,N) and M(N,S), with additional contributions from DP_{COOH}(O,S). STM reveals adsorption at Ti sites on terraces together with a pronounced preference for step edges, indicating that undercoordinated sites play an important role in the adsorption process. XPS and FT-IRRAS further show that the amino group is predominantly unprotonated on anatase, which is consistent with direct N-Ti coordination and therefore with the dominance of mixed adsorption modes rather than zwitterionic or purely carboxylate bridging ones. The S 2p data additionally demonstrate a larger fraction of sulfur directly bonded to Ti on anatase than on rutile. DFT supports this interpretation by identifying M(N,S) and DP_{COOH}(O,N) as the most stable and nearly degenerate configurations, whereas DP_{COOH}(O,S) is less favorable and zwitterionic forms make only a minor contribution. In other

words, whereas rutile $\text{TiO}_2(110)$ stabilizes $\text{DP}(\text{O},\text{O})/\text{ZW}(\text{O},\text{O})$, anatase $\text{TiO}_2(101)$ clearly favors mixed adsorption, above all $\text{DP}_{\text{COOH}}(\text{O},\text{N})$, together with $\text{M}(\text{N},\text{S})$.

The comparison between the two TiO_2 polymorphs therefore leads to an important general conclusion. The shorter Ti-Ti spacing on rutile $\text{TiO}_2(110)$ makes bridging carboxylate coordination particularly favorable, whereas the larger Ti-Ti spacing on anatase $\text{TiO}_2(101)$ reduces the preference for pure (O,O) binding and allows mixed geometries involving the amino group, and to some extent sulfur, to compete successfully. This facet dependence is one of the main mechanistic outcomes of the thesis. It shows that adsorption on TiO_2 must be understood not only in terms of molecular functional groups, but also in terms of the geometric constraints imposed by the oxide surface

The second major result of this thesis concerns the photooxidation of cysteine on anatase $\text{TiO}_2(101)$. Under UV irradiation in air, cysteine does not undergo broad, non-selective decomposition of the entire molecule. Instead, the oxidation proceeds selectively through the thiol group, while the amino functionality remains essentially intact. XPS shows the disappearance of the initial thiol and S-Ti related sulfur species and the appearance of new sulfur components at higher binding energy, consistent with a stepwise oxidation sequence. After short irradiation times, an intermediate sulfur signal appears at around 166.5 eV, assigned to partially oxidized sulfur species, that is, a mixture of sulfenic- and sulfinic-like intermediates. At longer irradiation times, this intermediate disappears and the sulfur signal is dominated by the fully oxidized component at about 168.7 eV, assigned to sulfonic acid, indicating that cysteine is ultimately converted into a cysteic acid-like surface product.

The mechanistic picture obtained from the DFT calculations provides a more detailed explanation for this transformation. Starting from the $\text{DP}_{\text{COOH}}(\text{O},\text{N})$ adsorption geometry, molecular O_2 first adsorbs at a $\text{Ti}_{5\text{c}}$ site and is activated under photoexcitation to a superoxo species, accompanied by deprotonation of the thiol and initial sulfur oxidation. The system then evolves through further oxygen activation and oxygen transfer steps, producing progressively more oxidized sulfur intermediates. The calculations indicate that the pathway proceeds through sulfur oxidation states corresponding first to a thiolate-like oxidized species, then to SO^- or SO_2H -type intermediates, and finally to the fully oxidized $-\text{SO}_3\text{H}$ product. Importantly, the calculations show that oxidation at nitrogen is energetically less favorable than oxidation at sulfur, which explains why the N 1s signal remains essentially unchanged throughout irradiation.

The investigation of L-asparagine offers a complementary perspective. Here again, the comparison between rutile and anatase is central. On both surfaces, asparagine adsorbs through a deprotonated carboxylate group, while the side-chain amide remains intact. However, the balance between adsorption geometries differs clearly between the two polymorphs. On rutile $\text{TiO}_2(110)$, the dominant adsorption mode is $\text{DP}(\text{O},\text{O})/\text{ZW}(\text{O},\text{O})$, that is, carboxylate bridging along the $\text{Ti}_{5\text{c}}$ rows. STM shows mainly row-confined protrusions consistent with this geometry, and the N 1s spectra exhibit a comparatively stronger NH_3^+ contribution, indicating that a larger fraction of molecules is present in configurations where the amino group does not bind directly to Ti and therefore remains available for protonation. Rutile $\text{TiO}_2(110)$ therefore stabilizes $\text{DP}(\text{O},\text{O})/\text{ZW}(\text{O},\text{O})$ much more strongly than anatase $\text{TiO}_2(101)$.

On anatase $\text{TiO}_2(101)$, by contrast, asparagine shows a significantly higher proportion of mixed DP(O,N) adsorption. STM resolves not only row-aligned adsorbates attributable to (O,O) coordination, but also a substantial number of diagonally oriented species, which are consistent with DP(O,N) binding across neighboring surface rows. XPS supports this interpretation by showing a relatively stronger neutral NH_2 contribution and a weaker NH_3^+ component than on rutile, indicating that the amino group is more often directly involved in surface coordination and therefore less prone to protonation. FT-IRRAS confirms deprotonated carboxylate binding on both polymorphs, but the subtle spectral differences between anatase and rutile are fully consistent with a higher fraction of mixed (O,N) binding on anatase.

Taken together, the results for asparagine confirm that the facet dependence identified for cysteine is not an isolated case caused by the thiol (-SH) functional group, but a more general characteristic of amino acid adsorption on TiO_2 . Rutile $\text{TiO}_2(110)$ preferentially stabilizes row-confined bridging carboxylate adsorption, whereas anatase $\text{TiO}_2(101)$ more readily accommodates mixed geometries involving the amino group.

This thesis shows that the interaction of amino acids with TiO_2 is governed by an interplay of three factors, the spacing and arrangement of surface Ti sites, the protonation flexibility of the molecule, and the availability of additional donor groups beyond the carboxylate. For cysteine, this leads to coexistence of DP(O,O)/ZW(O,O), DP(O,N), and DP(O,S) on rutile, but mainly $\text{DP}_{\text{COOH}}(\text{O,N})$ and M(N,S) on anatase. For asparagine, it leads to a surface dependent competition between DP(O,O)/ZW(O,O) and DP(O,N), with rutile $\text{TiO}_2(110)$ favoring the former and anatase $\text{TiO}_2(101)$ favoring a higher proportion of the latter.

The implications of this work extend beyond the individual systems studied here. Since amino acids represent the functional units of proteins, the adsorption motifs and transformation pathways identified in this thesis provide an atomic-level understanding of how more complex biomolecules interact with TiO₂ surfaces. In particular, the sulfur selective oxidation pathway established for cysteine on anatase suggests that photocatalytic inactivation of proteins may begin through selective modification of especially vulnerable residues rather than through immediate, non-specific degradation of the whole structure. At the same time, the facet dependent adsorption geometries of both cysteine and asparagine show that the polymorph composition of TiO₂ surfaces affects not only how biomolecules are anchored, but also which functional groups are exposed to subsequent chemical transformation.

Several future directions follow naturally from these results. A first step would be to extend the same combined STM, XPS, FT-IRRAS, and DFT methodology to other amino acids containing hydroxyl, aromatic, acidic, or basic side chains. This would allow the adsorption rules identified here to be generalized across a broader range of biomolecular functionalities. A second important direction would be to investigate more systematically the role of step edges and other undercoordinated sites, especially on anatase TiO₂(101), where they clearly contribute to adsorption and may also influence photocatalytic reactivity. A third step would be to bridge the gap between UHV surface science and more realistic photocatalytic conditions by introducing controlled water and oxygen environments and by following reaction intermediates under illumination with greater temporal resolution for example by performing AP-XPS, or ATR-IR. In addition, electrocatalytic studies could help identify possible transformation pathways, which can be followed by liquid chromatography. Finally, extending these studies from isolated amino acids

to short peptides would provide a direct link between the present molecular-level understanding and the behaviour of larger biological structures at photocatalytic oxide interfaces.

Appendix 1: Supplementary Information of Unravelling the Role of the Multi-Functional Groups in the Adsorption of L-Cysteine on Rutile TiO₂(110)

Supporting Materials for

Unravelling the Role of the Multi-Functional Groups in the Adsorption of L-Cysteine on Rutile TiO₂(110)

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S.I. 1 EXPERIMENTAL AND COMPUTATIONAL DETAILS

1.1 Crystal Preparation methods:

The single crystalline rutile TiO₂(110) sample, 8 mm × 8 mm × 2 mm (Surface Net Ltd.), was subjected to multiple cycles of argon ion sputtering (1 keV, 10⁻⁶ mbar Ar⁺, 5 minutes) and subsequent annealing. The annealing process was carried out at 1000 K under back pressure of 10⁻⁶ mbar of O₂ for 10 minutes, followed by an additional 10 minutes annealing under ultra-high vacuum (UHV) at the same temperature. This careful preparation resulted in a flat and uncontaminated rutile surface with minimal Ti³⁺ defect sites as it was reported by Diebold et al. (1). The surface was prepared until a clean, well-defined (1 × 1) low energy electron diffraction (LEED) pattern was achieved, and XPS analysis confirmed the absence of contaminants in O 1s and C 1s core levels, as well as an almost defect free surface shown in the minimal content of Ti³⁺ as shown in **Figure S1**.

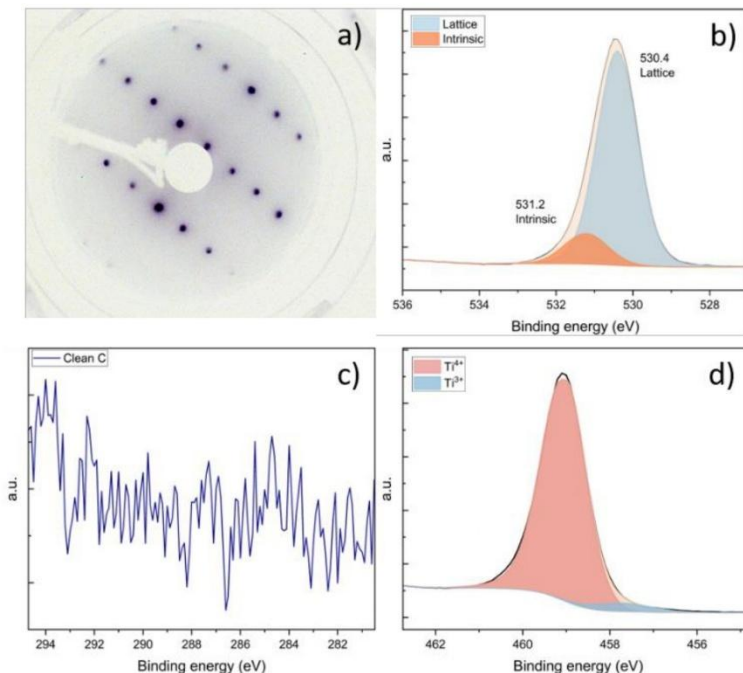


Figure S1. (a) LEED pattern of rutile (110) after preparation under UHV taken at 100 eV. Experimental and deconvoluted XP spectra of the clean rutile (110) surface (b) O 1s, (c) C 1s, (d) Ti 2p 3/2.

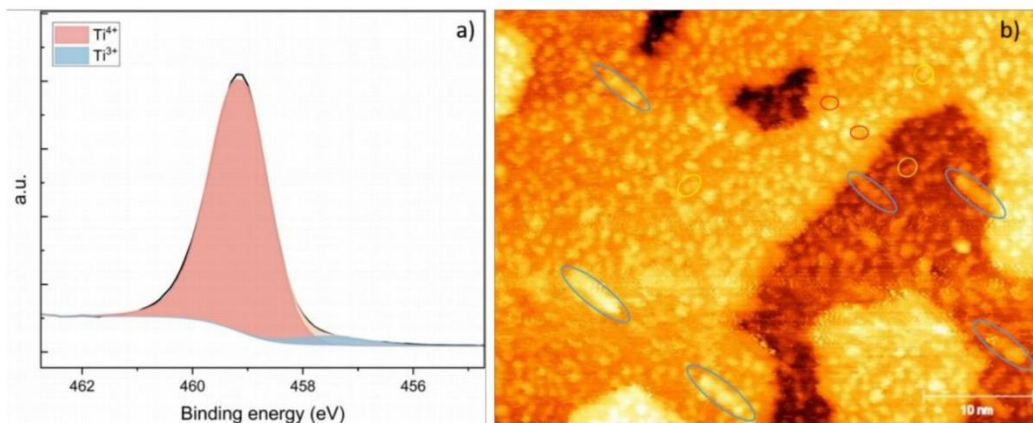


Figure S2. (a) XP spectra of Ti 2p 3/2 region after cysteine evaporation. (b) STM image of rutile (110) surface measured after dosing 50 L of cysteine at room temperature on a pre-cleaned surface. 35x45 nm; image taken with 1.7 V of bias voltage and 0.3 nA current.

1.7 Computational details:

Density Functional Theory (DFT) calculations were performed using the plane-wave-based Quantum ESPRESSO (QE) package (7, 8). Ultrasoft pseudopotentials (9) were employed to model the electron-ion interactions, with energy cutoffs of 52 Ry for kinetic energy and 575 Ry for charge density expansion, applied in all calculations. The Perdew-Burke-Ernzerhof (PBE) functional (10) was used for the electron exchange-correlation, while van der Waals interactions were included using the DFT-D3 correction (11). A Hubbard U value of 3 eV was applied to Ti, in accordance with previous literature (12).

The rutile $\text{TiO}_2(110)$ surface was modelled using a slab of four O-Ti-O trilayers, with the oxygen and titanium atoms in the bottom trilayer (only the bottom oxygen in this layer was allowed to relax) fixed at their bulk positions during geometry optimization to simulate a semi-infinite solid. To vary the number of five-coordinated titanium (Ti_{5c}) rows, two supercell models were employed: a $c(4 \times 2)$ surface cell for the case with one Ti_{5c} row, and a $c(8 \times 2)$ cell for the case with two Ti_{5c} rows. A vacuum space of at least 13 Å was included in the direction perpendicular to the surface to prevent interactions between adjacent periodic images. Ball-and-stick models were visualized using VESTA software (13).

Geometry optimizations were carried out starting from a range of initial configurations, generated by manually placing the cysteine molecule on the rutile surface, guided by the expected chemical reactivity of its functional groups, namely $-\text{NH}_2$, $-\text{COOH}$, and $-\text{SH}$, on a polar oxide surface. All geometry optimizations were performed at the Γ point. To verify convergence, additional tests using a denser $4 \times 4 \times 1$ k-point mesh were carried out on all configurations presented in Figures 3abc, 4b, and 6ab of the main text, revealing tiny differences in both geometries and energetics.

The adsorption energies (ΔE_{ads}) in vacuum for cysteine on the $\text{TiO}_2(110)$ surface were calculated using the following formula:

$$\Delta E_{\text{ads}} = E_{n \text{ cys}/\text{TiO}_2} - (n E_{\text{cys}} + E_{\text{TiO}_2})$$

where $E_{n \text{ cys}/\text{TiO}_2}$ is the total energy of the optimized system with n adsorbed cysteine molecules (where $n = 1$ or 2), E_{cys} is the total energy of an isolated cysteine molecule in the gas phase, and E_{TiO_2} is the total energy of the optimized $\text{TiO}_2(110)$ surface without any adsorbed cysteine molecules. For cases where the adsorption of a single cysteine molecule was computed in the presence of water molecules, the adsorption energies were determined as follows:

$$\Delta E_{\text{ads}} = E_{\text{cys}+n\text{H}_2\text{O}/\text{TiO}_2} - (E_{\text{cys}} + n E_{\text{H}_2\text{O}} + E_{\text{TiO}_2})$$

where $E_{\text{cys}+n\text{H}_2\text{O}/\text{TiO}_2}$ is the total energy of the system with a cysteine molecule (in its deprotonated or zwitterionic form) adsorbed on the TiO_2 surface in the presence of n water molecules, and $E_{\text{H}_2\text{O}}$ is the total energy of a water molecule in the gas phase.

In the case of cystine formation, where a disulphide (S-S) bond is formed between two cysteine molecules, we also consider the possibility of the formation of an H_2 molecule in the gas phase. In this case, the adsorption energy for cystine on the $\text{TiO}_2(110)$ surface is calculated using the following equation:

$$\Delta E_{\text{ads,cystine}} = E_{\text{cystine}/\text{TiO}_2} + E_{\text{H}_2} - (2 E_{\text{cys}} + E_{\text{TiO}_2})$$

where $E_{\text{cystine/TiO}_2}$ is the total energy of the optimized system with cystine adsorbed on the TiO_2 surface, E_{H_2} is the total energy of the H_2 molecule in the gas phase, E_{cys} is the energy of an isolated cysteine molecule in the gas phase, and E_{TiO_2} is the energy of the $\text{TiO}_2(110)$ surface without any adsorbed molecules.

XPS calculations were performed within the ΔSCF method (14) with the use of additional pseudopotentials for each inequivalent C, N, O or S atom, generated removing an electron from the core 1s (C, N, O) or 2p (S) orbitals. For these simulations, the plane-waves basis-set needed to be enlarged to 74 and 575 Ry. Such an approach does not allow the calculation of an absolute value of the binding energies (BEs), but just their difference with respect to a chosen reference, or core level shift (CLS). To be able to compare the CLSs of different structures contained in distinct simulation cells, we placed one CH_4 , N_2 , O_2 or H_2S reference molecule at a time for any C, N, O and S photoexcited atom, respectively. In order to minimize the interaction of these molecules with the simulated system, we inserted them in the vacuum region, with a distance of at least 12 Å from any other atom and enlarged the supercell size accordingly.

The vibrational frequencies of cysteine adsorbed on $\text{TiO}_2(110)$ were calculated within the harmonic approximation. Numerical Hessian matrices were constructed by applying finite displacements (± 0.02 a.u.) along all three Cartesian directions from the equilibrium positions and computing the corresponding atomic force components. This procedure was applied to both the gas-phase and adsorbed configurations. The resulting Hessian matrices were diagonalized at the Γ point to obtain the vibrational frequencies associated with each normal mode. To decouple the motion of relaxed atoms from those constrained to their bulk positions, the Hessian matrix elements involving atoms constrained to simulate the bulk were set to zero.

Thanks to the computed vibrational frequencies, the free energies (G) of cysteine adsorbed on $\text{TiO}_2(110)$ at 298.15 K were obtained by correcting the electronic energies (E) for zero-point energy (ZPE), thermal contributions to the enthalpy ($\int C_p dT$), and the vibrational entropy (S_{vib}), according to the following expression:

$$G = E + \text{ZPE} + \int C_p dT - TS_{\text{vib}}$$

For the gas-phase cysteine molecule, the ideal gas approximation was applied, assuming a standard pressure of 1 bar.

Finally, atomic charge analysis was performed using the Hirshfeld method (15) and non-covalent interaction (NCI) analysis was carried out using the Critic2 code (16)

S.I. 2 Calculated binding geometries and energies for DP-Cysteine on rutile (110) at low and high coverage

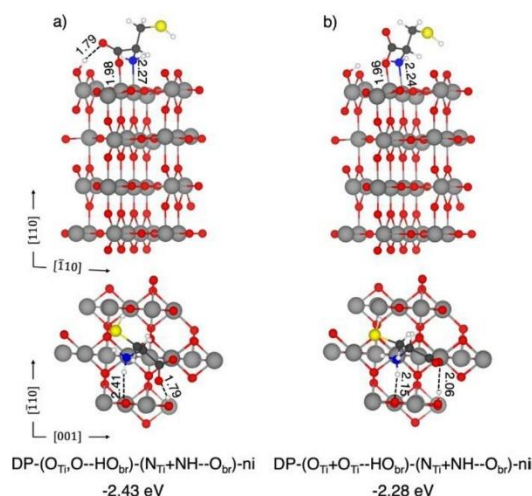


Figure S3. Structures of deprotonated cysteine adsorbed on rutile TiO_2 (110) surface. (a) The newly optimized $\text{DP}-(\text{O}_{\text{Ti}},\text{O}--\text{HO}_{\text{br}})-(\text{N}_{\text{Ti}},\text{NH}--\text{O}_{\text{br}})-\text{ni}$ with a H-bond between the HO_{br} and the unbound carboxylate O atom, and (b) $\text{DP}-(\text{O}_{\text{Ti}}+\text{O}_{\text{Ti}}--\text{HO}_{\text{br}})-(\text{N}_{\text{Ti}}+\text{NH}--\text{O}_{\text{br}})-\text{ni}$, based on the structure calculated by Muir and Idriss with a H-bond between the HO_{br} and the Ti-bound carboxylate O atom. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds and other electrostatic interactions. Adsorption energies (in eV) calculated with PBE+U and relevant bond length (values in Å) are reported.

Table S1. Adsorption energy values (in eV) calculated using PBE without and with Hubbard U correction for cysteine molecules adsorbed on rutile TiO₂(110) surface.

ΔE_{ads} (eV)	Figure	PBE-D3	PBE-D3+U
DP-(O _{Ti} ,O _{Ti})-ni-(HS--HO _{br})	1a	-1.90	-2.08
DP-(O _{Ti} +O _{Ti} --HO _{br})-(N _{Ti} +NH--O _{br})-ni	S3b	-2.08	-2.28
DP-(O _{Ti} ,O--HO _{br})-(N _{Ti} +NH--O _{br})-ni	1b	-2.26	-2.43
biDP-(O _{Ti} ,O--HO _{br})-ni-(S _{Ti})	1c	-1.79	-2.04
DP-(O _{Ti})-ni-(HS _{Ti})	1d	-1.06	-1.19
ZW-(O _{Ti} ,O _{Ti})-ni-(SH--O _{br})	4a	-1.75	not found

Table S2. Adsorption energy values (in eV) calculated using PBE with and without Grimme D3 dispersion correction for cysteine molecules adsorbed on rutile TiO₂(110) surface, compared with those obtained from in a previous work.

ΔE_{ads} (eV)	PBE-D3	PBE	PBE (Muir and Idriss)
DP-(O _{Ti} ,O _{Ti})-ni-(HS--HO _{br})	-1.90	-1.38	-1.47
DP-(O _{Ti} +O _{Ti} --HO _{br})-(N _{Ti} +NH--O _{br})-ni	-2.08	-1.33	-1.39

This result is in contrast with what reported in a previous study Muir and Idriss (17) where the (0,0) was indicated as the best adsorption mode. This is due to two reasons: 1) in that work a different (O)-(N) structure was proposed (DP-(O_{Ti}+O_{Ti}--HO_{br})-(N_{Ti}+NH--O_{br})-ni in **Figure S3b**) than the one found in the present work (DP-(O_{Ti},O--HO_{br})-(N_{Ti}+NH--O_{br})-ni in **Figure 1b**), which is more stable by -0.15 eV. The difference is related to the O atom involved in the H-bond. 2) The second reason is the lack of dispersion interactions in the DFT study by Muir and Idriss as we proved with some additional calculations without the Grimme correction in **Table S2**.

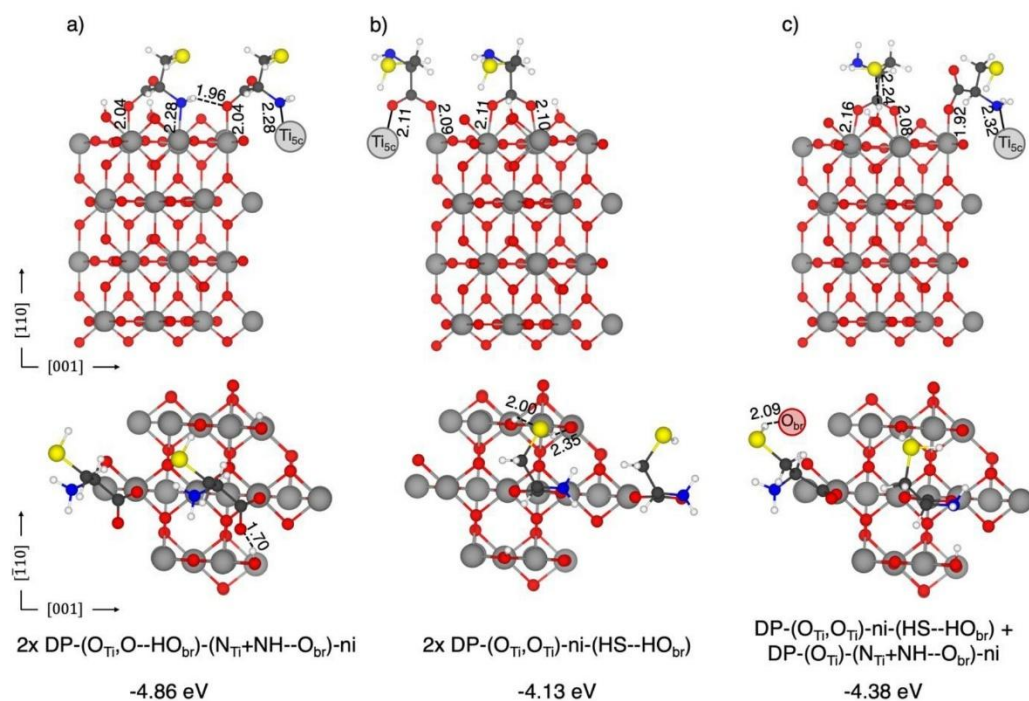


Figure S4. High coverage cysteine adsorption on rutile TiO₂(110) surface. (a) Two cysteine molecules in the DP-(O_{Ti},O--HO_{br})-(N_{Ti}+NH--O_{br})-ni configuration, (b) two in the DP-(O_{Ti},O_{Ti})-ni-(HS--HO_{br}) configuration, and (c) one in the DP-(O_{Ti})-(N_{Ti}+NH--

O_{br})-ni configuration with one in the DP-(O_{Ti}O_{Ti})-ni-(HS--HO_{br}) configuration are adsorbed on the rutile TiO₂(110) supercell slab model. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Adsorption energies (in eV) calculated with PBE-D3+U and relevant bond length (values in Å) are reported.

Table S3. Adsorption energy values (in eV) calculated using PBE-D3 without and with Hubbard U correction for cysteine molecules adsorbed on rutile TiO₂(110) surface at high coverage.

	PBE-D3		PBE-D3+U	
	ΔE_{ads} (eV)	ΔE_{ads} (eV/cys)	ΔE_{ads} (eV)	ΔE_{ads} (eV/cys)
2x DP-(O _{Ti} O _{Ti})-ni-(HS--HO _{br})-(N _{Ti} +NH--O _{br})-ni	-4.52	-2.26	-4.86	-2.43
2x DP-(O _{Ti} O _{Ti})-ni-(HS--HO _{br})	-3.79	-1.89	-4.13	-2.06
DP-(O _{Ti} O _{Ti})-ni-(HS--HO _{br}) + DP-(O _{Ti})-(N _{Ti} +NH--O _{br})-ni	-4.03	-2.01	-4.38	-2.19

S.I. 3 Core Level shifts and XP fitting information

3.1 Core level shifts information:

We focused on the DP-(O_{Ti}O_{Ti})-ni-(HS--HO_{br})-ni, DP-(O_{Ti}O_{Ti})-ni-(HS--HO_{br}) and biDP-(O_{Ti}O_{Ti})-ni-(S_{Ti})-(S_{Ti}) configurations, which are prototypes of the different geometries a cysteine monomer can adsorb on the rutile TiO₂(110) surface: DP (O)-(N), DP (O,O), DP (O)-(S). For the first structure, we considered also the corresponding high coverage configuration (2x DP(O)-(N)).

Table S4. CLSs (in eV) calculated for selected adsorption configurations, the isolated molecule and the rutile TiO₂(110) surface (for the topmost layer only) for different photoexcited core electron, each with respect to its reference.

*: deprotonated OH.

** : we obtain the same CLS for the two molecules included in the supercell.

Edge	Atom type	DP (O)-(N)	DP (O,O)	DP (O)-(S)	2x DP (O)-(N)**	ZW (O,O) + H ₂ O	S-S dimer [001] (O)-(N)	Cys gas phase	TiO ₂ surface
C 1s	C-O	+2.8	+2.8	+2.8	+2.7	+2.9	+2.3/+2.2	+4.0	-
	C-N	+0.7	+0.8	+0.3	+0.6	+1.9	+0.7/+0.8	+1.4	-
	C-S	+0.3	+0.3	-0.5	+0.2	+0.7	+0.2/+0.0	+0.6	-
N 1s	NH ₂	-	-1.7	-2.0	-	-	-	-2.2	-
	NH ₂ -Ti _{5c}	-1.0	-	-	-1.3	-	-0.1/-0.3	-	-
	NH ₃ ⁺	-	-	-	-	+1.6	-	-	-
O 1s	O1-Ti	-1.1	-0.5	-0.9	-1.1	-0.2	-0.6/-0.8	-	-
	O2-Ti	-	-0.6	-	-	-0.4	-	-	-
	O2*	-1.2	-	-0.9	-1.4	-	-0.9/-1.1	-	-
	C-OH/C=O	-	-	-	-	-	-	+0.9/-1.1	-
	TiO ₂ O _{br}	-2.7	-2.7	-2.4	-2.5	-2.9	-0.6	-	-3.0
	TiO ₂ O _{br} 1H	-1.5	-1.4	-1.1/-1.6	-1.4	-	-0.6	-	-
	TiO ₂ O _{3c}	-2.3	-2.3	-2.1	-2.3	-2.3	-1.9	-	-2.4
S 2p	S-H	-0.7	-0.2	-	-0.7	-1.1	-	-0.8	-
	S-Ti	-	-	-2.5	-	-	-	-	-
	S-S	-	-	-	-	-	-0.5/-0.4	-	-

3.2 Peak fitting protocol:

For each core level, deconvolution started with the minimum set of chemically plausible components; an additional peak was introduced only when demanded by either the envelope shape or the residual trace.

C 1s: L-cysteine has three inequivalent carbon atoms (C-SH, C-NH₂, COOH), so three components were fitted. A fourth peak did not improve the residual and was discarded.

O 1s: On clean TiO₂(110), the line consists of a lattice-oxygen peak plus a shoulder from intrinsic defects. Adsorption leaves extra intensity at high binding energy. Adding one component assigns this to carboxylate oxygens and removes the mismatch.

S 2p: The S 2p level is a doublet (2p_{3/2}–2p_{1/2}, 1.2 eV split, 2 : 1 area). A single -SH doublet left a low BE shoulder. Introducing a second doublet assigned to surface bound thiolate (S-Ti) eliminates the shoulder and flattens the residual.

N 1s: A one peak fit produced an overly broad, asymmetric envelope. Splitting into neutral –NH₂ and protonated –NH₃⁺ components removed the asymmetry and gave a satisfactory residual.

Residual standard deviations are compiled in Table S5 and confirm that no further peaks are required.

Table S5. Results of the fitting for XPS data All peaks have been fitted using a Shirley background and a Asymmetric Lorentzian lineshape LA(30) that has been proofed adequate for lightly conductive oxides (18–20).

Edge	Surface	Atom type	Position (eV)	FWHM (eV)	Ratio	Residual STD
O 1s	Clean	Intrinsic	531.2	1.31	0.15	1.78
		Lattice	530.4	1.23	1	
	Adsorption	Intrinsic	531.2	1.29	0.17	
		Carboxylate	532.1	1.45	0.06	
Ti 2p	Clean	Ti4+	549.1	1.12	1	3.24
		Ti3+	457.8	1.59	0.5	
	Adsorption	Ti4+	459.1	1.15	1	
		Ti3+	457.6	1.9	0.05	
C 1s	Adsorption	C-O	289.1	1.38	1	0.97
		C-N	286.1	1.69	1.1	
		C-S	285.2	1.47	1.1	
S 2p _{3/2}	Adsorption	S-H	164.1	1.37	1	0.82
		S-Ti	161.7	1.8	0.27	
N 1s	Adsorption	NH ₂	400.1	1.5	1	0.52
		NH ₃ ⁺	401.5	1.5	0.6	

S.I. 4 Thermochemical Data

Table S6: Electronic and Gibbs free energies for cysteine adsorption on rutile. The corresponding desorption temperatures, estimated using the Redhead approximation, are reported in the last column.

	ΔE (eV)	ΔG (eV)	T_{des} (°C)
$DP-(O_{Ti}O--HO_{br})-(N_{Ti}+NH--O_{br})-ni$	-2.43	-1.64	246
$DP-(O_{Ti}O_{Ti})-ni-(HS--HO_{br})$	-2.08	-1.37	183
$biDP-(O_{Ti}O--HO_{br})-ni-(S_{Ti})$	-2.04	-1.22	146

S.I. 5 Calculated geometries and energies for cysteine dimers on Rutile (110)

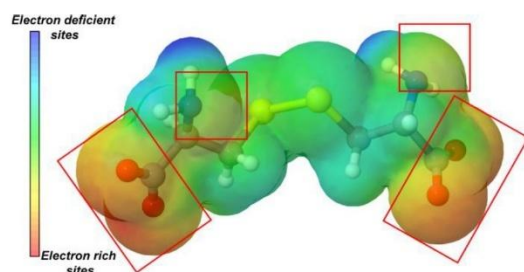


Figure S5. Molecular electrostatic potential (MEP) map of the gas-phase double deprotonated cystine. The MEP is plotted on a 0.0005 a.u. electron density isosurface. Electron-rich regions are highlighted with red boxes.

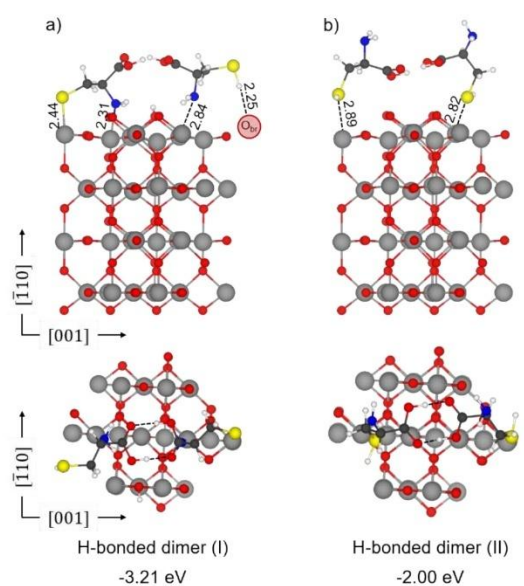


Figure S6. Structures of H-bonded cysteine dimers adsorbed on rutile $\text{TiO}_2(110)$ surface by (a) amino N atom coordination and (b) thiol S coordination to surface Ti_{5c} atoms. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds and other electrostatic interactions. Adsorption energies (in eV) calculated with PBE-D3+U and relevant bonds length (values in Å) are reported.

Table S7: Adsorption energy values (in eV) calculated using PBE-D3 and PBE-D3+U for cysteine dimers adsorbed on rutile $\text{TiO}_2(110)$. The corresponding structures are shown in **Figure 6** and **S6**.

E_{ads} (eV)	Figure	PBE-D3	PBE-D3+U
H-bonded dimer (I)	S6a	-3.00	-3.21
H-bond dimer (II)	S6b	-1.97	-2.00
S-S dimer [001] (O,O)	6a	-3.40	-4.07
S-S dimer [001] (O)-(N)	6b	-3.58	-4.21
S-S dimer [110] (O,O)	6c	-3.28	-3.87
S-S dimer [110] (O)-(N)	6d	-3.39	-3.98

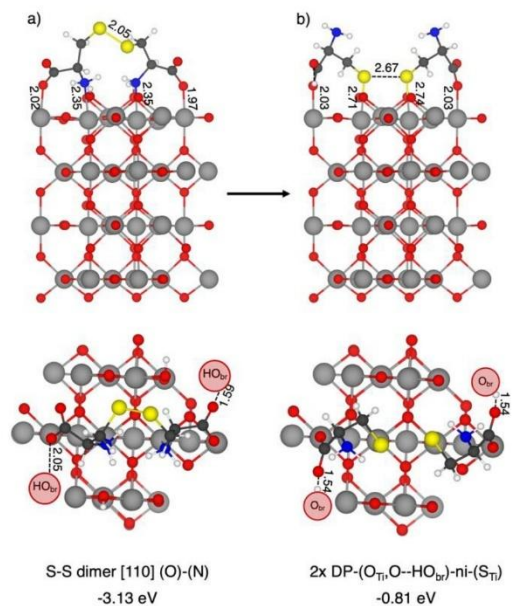


Figure S7. Structures of S-S cysteine dimers dissociation on rutile $\text{TiO}_2(110)$ surface. (a) S-S dimer adsorbed on the rutile $\text{TiO}_2(110)$ surface. (b) Cysteine monomers, obtained from S-S bond breaking of the dimer, adsorbed on the rutile $\text{TiO}_2(110)$ surface. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds and other electrostatic interactions. Adsorption energies (in eV) calculated with PBE-D3+U and relevant bonds length (values in Å) are reported.

S.I. 6 Charge and non-covalent interaction (NCI) analysis

Table S8: Atomic charges (in e) calculated using the Hirshfeld method for the most representative configurations discussed in the main text, along with gas-phase cysteine for comparison.

	Atomic charge (e)			
	O (-/Ti)	O (H/Ti)	N	S
Cys	-0.24	-0.15	-0.21	-0.07
DP-(O)-(N)	-0.20	-0.20	-0.10	-0.04
DP-(O,O)	-0.15	-0.16	-0.20	-0.01
DP-(O)-(S)	-0.16	-0.19	-0.20	-0.09
ZW-(O,O)	-0.15	-0.16	-0.02	-0.10
S-S dimer	-0.16/-0.16	-0.16/-0.17	-0.12/-0.20	-0.02/+0.01

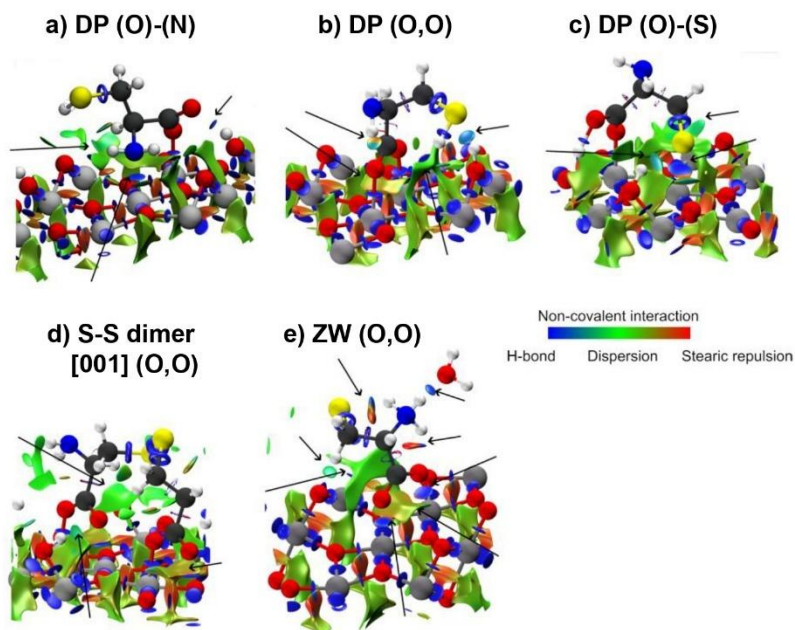


Figure S8. Non-covalent interaction (NCI) isosurfaces for representative configurations of the deprotonated, S-S dimer, and zwitterionic cases, as described in the main text. The color scale distinguishes the types of interactions: H bonding (blue), dispersion forces (green), and steric repulsion (red). Key interactions are highlighted with black arrows in each panel.

S.I. 7 STM population analysis

All high-quality STM images obtained under identical preparation and imaging conditions. Adsorbates were classified by visual inspection as either isolated molecules (red) or paired features consistent with cysteine dimers (yellow). Across the full image set we find an approximate **1 : 4 ratio of dimers to monomers**.

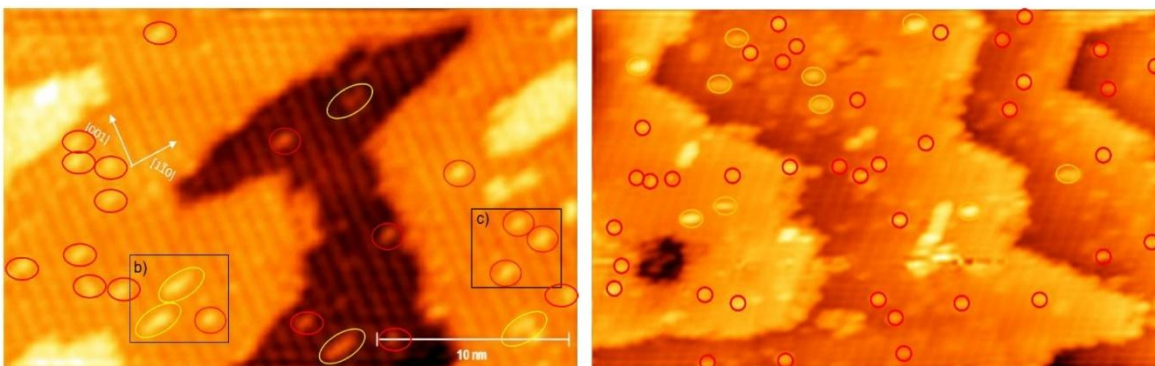


Figure S9. STM high resolution images of 0.1 L of cysteine at room temperature. left) is the image included in the main text with all individual adsorbates counted; right) different region of the sample from the same set.

S.I. 8 FT-IRRAS Background

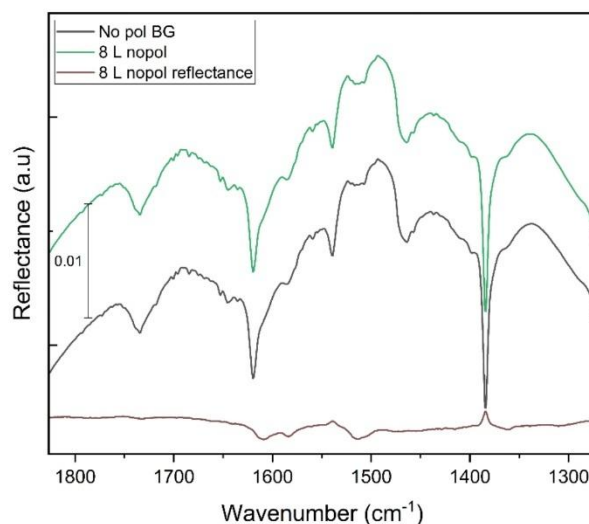


Figure S10. FT-IRRAS absolute data. In black is background used as reference, in green the spectra right after adsorption of 8L of cysteine and in brown the reflectance measured as $\Delta R/R_0$.

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Appendix 2: Supplementary Information from Adsorption and Sulphur-Selective Photooxidation of Cysteine on Anatase TiO₂(101)

Supporting Materials for

Adsorption and Sulphur-Selective Photooxidation of Cysteine on Anatase TiO₂(101)

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S.I. 1 EXPERIMENTAL AND COMPUTATIONAL DETAILS

1.1 Crystal Preparation methods:

The single crystalline anatase TiO₂ (101) sample, 8 mm × 8 mm × 2 mm (Surface Net Ltd.), was subjected to multiple cycles of argon ion sputtering (1 keV, 10⁻⁶ mbar Ar⁺, 5 minutes) and subsequent annealing. The annealing process was carried out at 700 K under back pressure of 10⁻⁶ mbar of O₂ for 10 minutes, followed by an additional 10 minutes annealing under ultra-high vacuum (UHV) condition at 950 K. This careful preparation resulted in a flat and uncontaminated anatase surface as reported by (1) The surface was prepared until a clean, well-defined (1 × 1) low energy electron diffraction (LEED) pattern was achieved, and XPS analysis confirmed the absence of contaminants in O 1s and C 1s core levels.

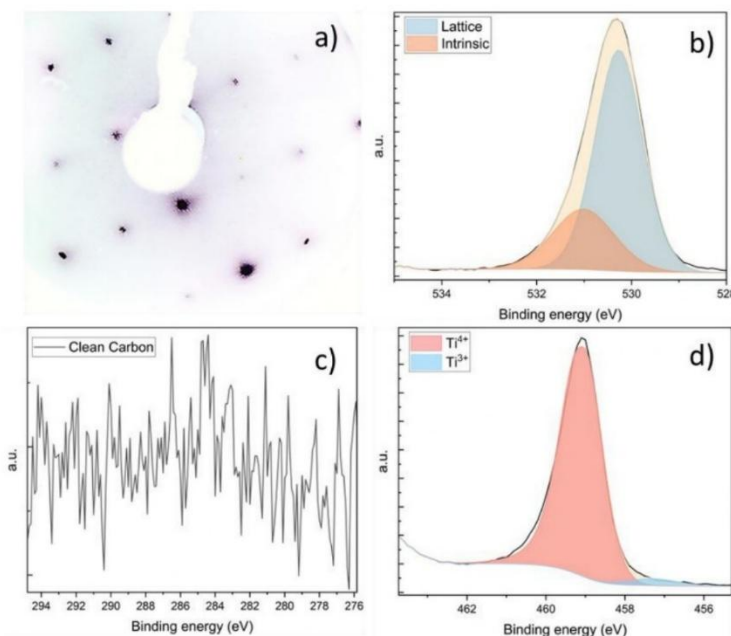


Figure S1. (a) LEED pattern of anatase TiO₂(101) after preparation under UHV taken at 100 eV. Experimental and deconvoluted XP spectra of the clean anatase (101) surface (b) O 1s, (c) C 1s, (d) Ti 2p 3/2.

1.2 Evaporation of cysteine:

Cysteine evaporation was performed in two different UHV sample preparation chambers. For XPS and STM measurements, evaporation occurred in a load lock connected to the STM chamber, with a base pressure in the low 10^{-9} mbar range. During XPS measurements, the sample had to be transferred post-evaporation through a tunnel connecting all equipment, maintaining a base pressure of low 10^{-9} mbar, requiring around 15 minutes for the full transfer process.

The FT-IRRAS chamber, also with a base pressure of low 10^{-9} mbar, is equipped with an evaporation line and a nozzle directed at the sample, allowing deposition and measurement without relocating the sample from the measurement stage.

For all experiments, the gas line containing cysteine was pumped, baked out, and heated to 130 °C during exposure. Temperature measurements were taken using a type K thermocouple attached to the glass tube.

1.3 X-ray photoelectron spectroscopy:

All XPS measurements were conducted at the DESY Nanolab at the Centre for X-ray and Nano Science, DESY, Hamburg (2). The instrument is equipped with a monochromated Al K_{α} source (1.486 keV) and a Phoibos 150 hemispherical energy analyzer, operating under a base pressure of low 10^{-10} mbar. Data analysis was performed using CasaXPS software.

1.4 Scanning tunneling microscopy:

STM images were acquired using a combined STM/AFM system under UHV conditions at a pressure of low 10^{-11} mbar. Measurements were performed in constant current mode at room temperature, employing a tungsten tip. Scanning parameters included voltage ranges from 0.8 V to 1.2 V and current ranges from 0.1 nA to 0.3 nA.

1.5 Fourier-Transformed Infrared Spectroscopy:

FT-IRRAS spectrometer (Bruker Vertex V80) is connected to a UHV chamber with a base pressure of low 10^{-9} mbar. Each IR spectrum was taken in reflection mode with 512 scans at a resolution of 2 cm^{-1} .

1.6 Thickness estimation:

The thickness of the cysteine layer (d_{meas}) was estimated by calculating the area intensity of the TiO_2 $2p_{3/2}$ peak using Formula 1.

$$I_M = I_0 \cdot e^{-\frac{d_{\text{meas}}}{\lambda}}$$

In this formula, I_M represents the area of the $\text{Ti}_{2p} 3/2$ peak in anatase $\text{TiO}_2(101)$ after cysteine adsorption, I_0 denotes the area of the same peak for the clean surface, and λ stands for the effective attenuation length (EAL) of electrons in L-cysteine, extracted from the NIST Database 82 (3)). The electrons in $\text{Ti } 2p_{2/3}$ have a kinetic energy of 1027.56 eV and have an asymmetry parameter (β) of 1.41. We consider the stoichiometric coefficients for cysteine: $\text{H} \rightarrow 7$, $\text{C} \rightarrow 3$, $\text{N} \rightarrow 1$, $\text{O} \rightarrow 2$, $\text{S} \rightarrow 1$; it has 42 valence electrons, a band-gap energy of 4.62 eV and a density of 1.68 g/cm^3 . (4). The incidence and emission angles of the XPS set up are 55° and 0° , correspondingly.

The average EAL for $\text{Ti } 2p_{3/2}$ $E_k = 1027.56\text{ eV}$ is recorded as $\text{EAL} = 27.4\text{ \AA}$, providing a practical average EAL value applicable for thicknesses up to 5 nm. I_0 has a value of 44300 counts per seconds cps and I_M has 38000 cps.

The calculated total thickness approximates to 0.4 nm, signifying nearly half a monolayer of cysteine, assuming its dimensions as $6.4\text{ \AA}$ in length and $3.7\text{ \AA}$ in width (5). This implies that even after dosing 500 L of molecules, a saturation level is attained that impedes the formation of multilayers at standard room temperature.

Figure S2 presents a STM image of an anatase (101) surface nearly fully saturated with 50 L of cysteine. At this coverage the whole surface is fully covered, however we do not observe any bi- or multilayer formations as it was also calculated in XPS. This suggests that there is a limit below a monolayer in which cysteine can adsorb on TiO_2 at room temperature. At this coverage, no distinct preferred orientation or ordered molecular layer of cysteine can be discerned on the surface.

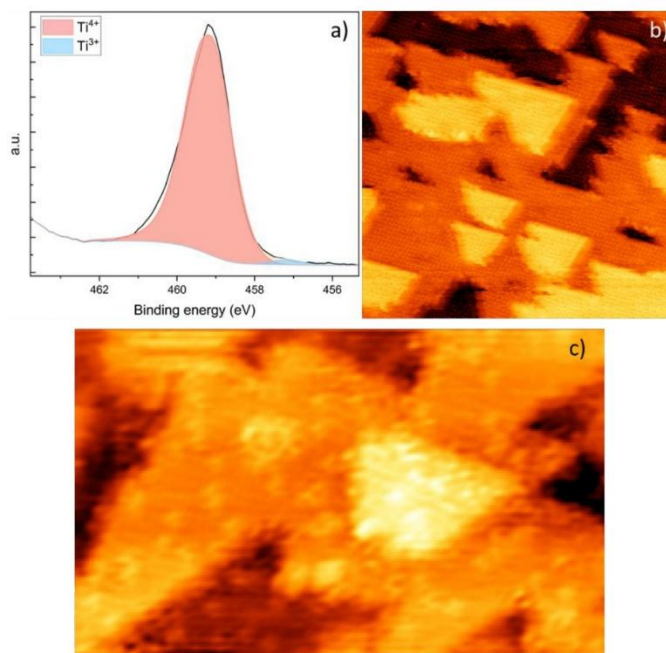


Figure S2. (a) XPS spectra of Ti 2p 3/2 region after cysteine evaporation. (b) STM image of clean anatase (101). 35x35 nm; image taken with 1.05 V of bias voltage and 0.3 nA current. (c) STM image of anatase (101) surface measured after dosing 50 L of cysteine at room temperature on a pre-cleaned surface. 20x10 nm; image taken with 1.1 V of bias voltage and 0.1 nA current.

1.7 Oxidation procedure

The sample was transferred out of the XPS chamber through a load-lock connected to the main UHV system. The irradiation procedure was carried out under atmospheric pressure. UV illumination was provided by a commercial lamp with a central wavelength of 365 nm, positioned approximately 10 cm from the sample surface. The irradiance at the sample was estimated to be $\sim 850 \mu\text{W}\cdot\text{cm}^{-2}$, corresponding to a photon flux of $\sim 1.5 \times 10^{15} \text{ photons}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ at 365 nm. Illumination conditions of this magnitude are comparable to those commonly employed in TiO_2 photocatalytic oxidation studies ($\sim 0.5\text{--}2 \text{ mW}\cdot\text{cm}^{-2}$) (6, 7).

1.8 Computational details:

Density Functional Theory (DFT) calculations were carried out using the plane-wave-based Quantum ESPRESSO package (8, 9). Electron-ion interactions were described with ultrasoft pseudopotentials (10), applying energy cutoffs of 52 Ry for the kinetic energy and 575 Ry for the charge density in all simulations. The Perdew-Burke-Ernzerhof (PBE) (11) was used for the electron exchange-correlation, and van der Waals interactions were included via the DFT-D3 correction (12). A Hubbard U value of 3.9 eV was applied to Ti atoms, following previous literature (13-18).

The anatase $\text{TiO}_2(101)$ surface was modelled using a slab of three O-Ti-O trilayers, and a (1x2) supercell model with two Ti_{5c} rows. The oxygen and titanium atoms in the bottom layer fixed at their bulk positions during geometry optimization to simulate a semi-infinite solid and a vacuum space of at least 25 Å was included in the direction perpendicular to the surface to prevent interactions between adjacent periodic images. All geometry optimizations were performed at the Γ point. Ball-and-stick models were visualized using VESTA software (19).

The adsorption energies (ΔE_{ads}) in vacuum for cysteine on the $\text{TiO}_2(101)$ surface were calculated using the following formula:

$$\Delta E_{\text{ads}} = E_{\text{cys/TiO}_2} - (E_{\text{cys}} + E_{\text{TiO}_2})$$

S.I. 2 Optimized adsorption configuration on the anatase $\text{TiO}_2(101)$ surface

2.1 Molecular Geometries:

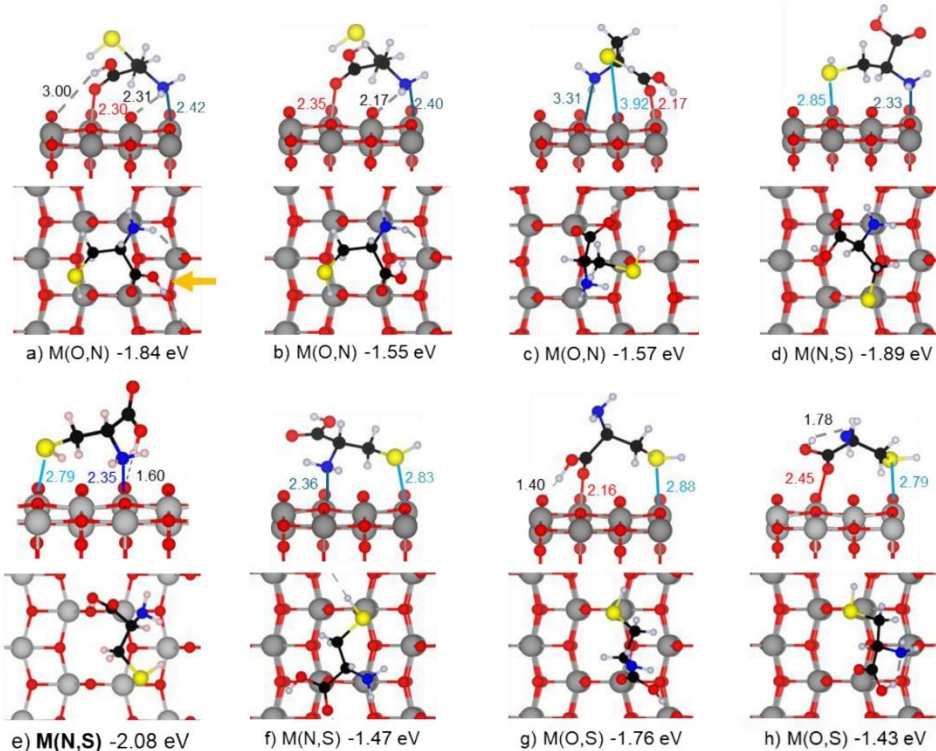


Figure S3. Side and top views of the optimized structures of molecular cysteine adsorption configurations on the anatase $\text{TiO}_2(101)$ surface, calculated using QE with the PBE+D3+U approach. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds. Adsorption energies (in eV) are reported below each structure, and selected bond lengths (in Å) are indicated. For clarity, only a portion of the supercell is shown.

2.2 Deprotonated Geometries:

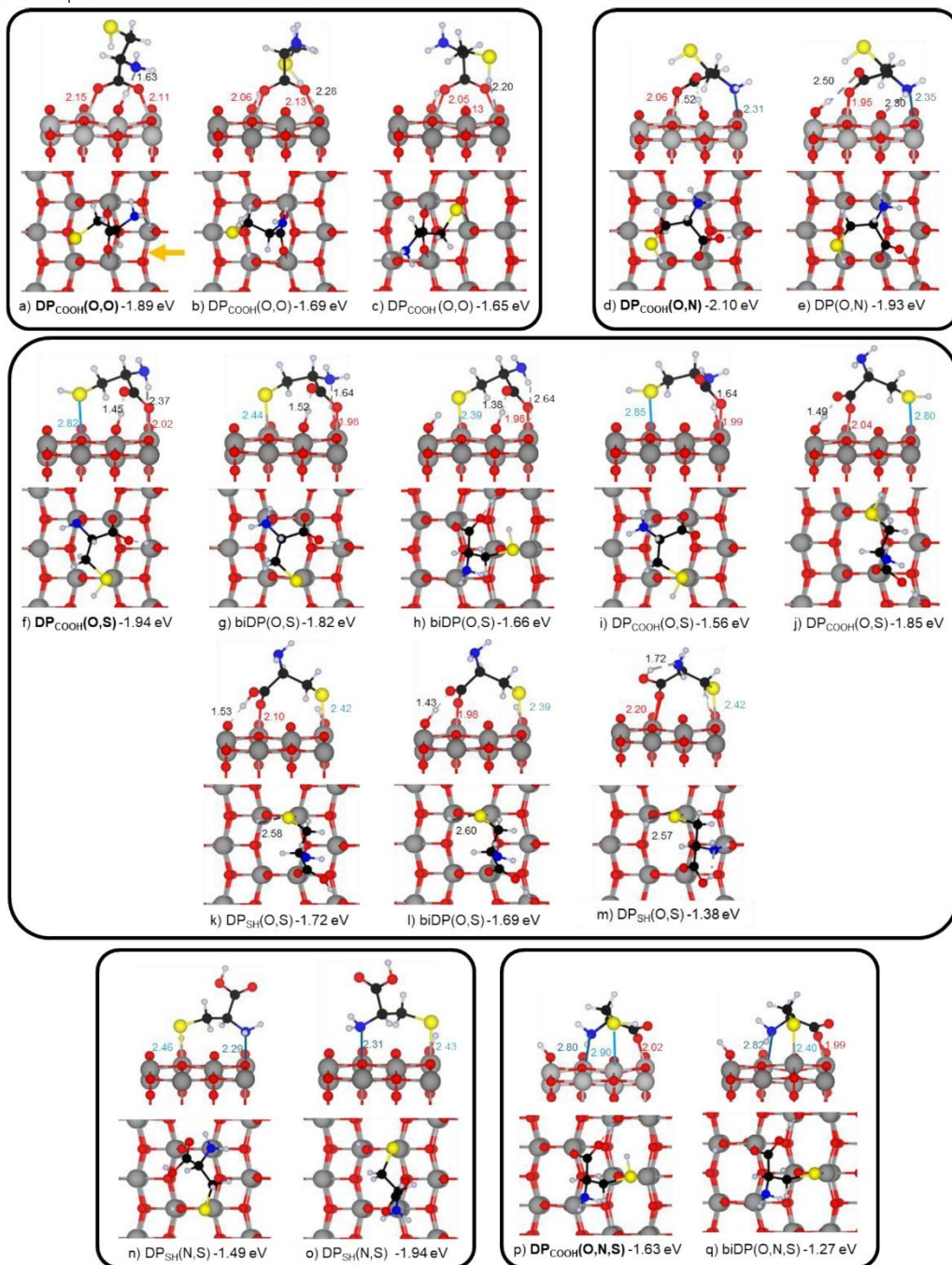


Figure S4. Side and top views of the optimized structures of deprotonated cysteine adsorption configurations on the anatase $\text{TiO}_2(101)$ surface, calculated using QE with the PBE+D3+U approach. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds. Adsorption energies (in eV) are reported below each structure, and selected bond lengths (in Å) are indicated. For clarity, only a portion of the supercell is shown.

2.3 Zwitterionic Geometries:

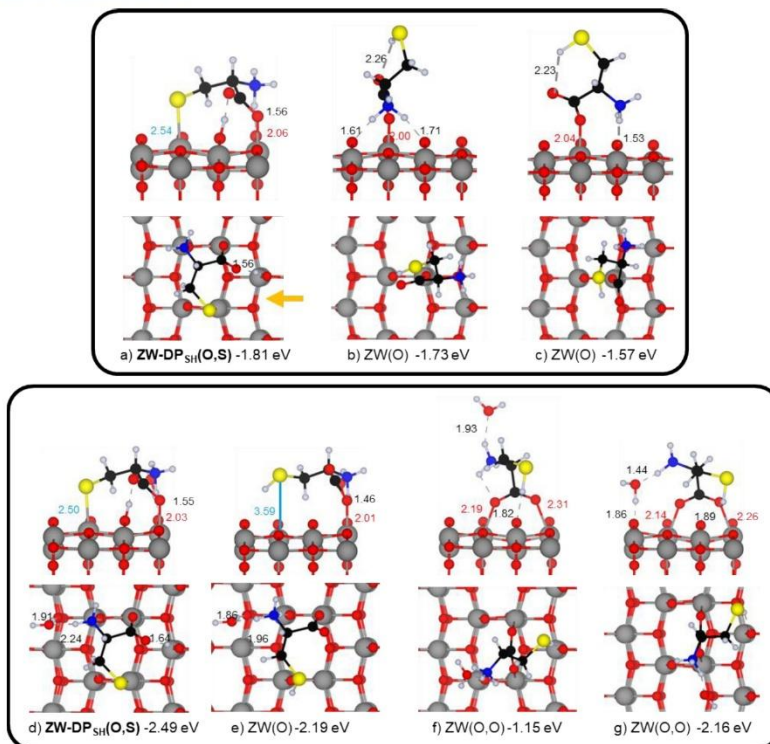


Figure S5. Side and top views of the optimized structures of zwitterionic cysteine adsorption configurations on the anatase $\text{TiO}_2(101)$ surface, calculated using QE with the PBE+D3+U approach. The top and bottom panels show the structures with and without one gas-phase water molecule, respectively. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. Dashed lines indicate hydrogen bonds. Adsorption energies (in eV) are reported below each structure, and selected bond lengths (in Å) are indicated. For clarity, only a portion of the supercell is shown.

2.4 Energy comparison between Geometries:

Table S1. Comparison of the relative energetic stability of the most stable molecular, deprotonated, and zwitterionic cysteine adsorption configurations. Calculations were performed using QE with PBE+U+D3 and CRY17 with HSE06+D3 (values in parentheses). Values in square brackets are taken from Pantaleone et al. for comparison with the present results (21). A hyphen indicates that the corresponding configuration was not found.

QE/PBE+U+D3 (CRY17/HSE06+D3)	Figure	ΔE (eV)	ΔE_{ads} (eV)
DP(O,N)	Figure 4c	0.00 (0.00) [+0.12]	-2.10 (-2.06)
M(N,S)	Figure 4a	+0.02 (+0.07) [+0.17]	-2.08 (-1.99)
ZW-DP _{SH} (O,S)	Figure 5a	+0.29 (+0.39)	-1.81 (-1.66)
ZW(O,O)		- (+0.29) [0.00]	- (-1.77)

S.I. 3 Core Level shifts and XP fitting information

3.1 Core level shifts information:

Table S2. CLSs (in eV) calculated for selected adsorption configurations and the isolated molecule for different photoexcited core electrons, each with respect to its reference.

		Scheme 1	Fig. 4a	Fig. 4b	Fig. 4c	Fig. 4d	Fig. 4e	Fig. 5a
Edge	Atom type	Cys gas-phase	M(N,S)	DP _{COOH} (O,O)	DP _{COOH} (O,N)	DP _{COOH} (O,S)	DP _{COOH} (O,N,S)	ZW- DP _{SH} (O,S)
C 1s	C-O	+3.7	+3.1	+3.0	+3.0	+2.8	+2.9	+3.0
	C-N	+1.3	+1.5	+1.1	+1.1	+0.9	+1.0	+1.9
	C-S	+0.8	+0.8	+0.7	+0.2	+0.2	+0.5	+0.4
N 1s	NH ₂	-2.3	–	-0.8	–	-1.8	–	–
	NH ₂ -Ti _{5c}	–	-0.7	–	-0.7	–	-1.5	–
	NH ₃ ⁺	–	–	–	–	–	–	+1.7
O 1s	O1-Ti	–	–	-0.6	-0.9	-1.0	-1.1	-0.7
	O2-Ti	–	–	-0.6	-1.1	-1.0	-1.2	-0.6
	C-OH/ C=O	+1.1/-1.0	-0.1/- 1.4	–	–	–	–	–
S 2p	S-H	-0.5	-0.4	-0.5	-0.9	-0.6	-0.8	–
	S-Ti	–	–	–	–	–	–	-2.5

3.2 Peak fitting protocol:

For each core level, deconvolution started with the minimum set of chemically plausible components; an additional peak was introduced only when demanded by either the envelope shape or the residual trace.

C 1s: L-cysteine has three inequivalent carbon atoms (C-SH, C-NH₂, COOH), so three components were fitted. A fourth peak (C-SO_x) was added only when necessary. During UV exposure at room temperature the C-S peak shifts towards lower binding energies while growing, indicating the deposition of adventitious carbon

O 1s: On clean TiO₂(101), the line consists of a lattice oxygen peak plus a shoulder from intrinsic defects. Adsorption leaves extra intensity at high binding energy. Adding one component assigns this to carboxylate oxygens and removes the mismatch.

S 2p: The S 2p level is a doublet (2p_{3/2}-2p_{1/2}, 1.2 eV split, 2 : 1 area). A single -SH doublet left a low BE shoulder. Introducing a second doublet assigned to surface bound thiolate (S-Ti) eliminates the shoulder and flattens the residual. After illumination a new high binding energy doublet appears at 168.7 eV, which is assigned to fully oxidized sulfur species (sulfonate like, -SO₃H). However, this component alone does not adequately reproduce the experimental line shape. An additional intermediate doublet at 166.5 eV is required.

N 1s: A one peak fit produced an overly broad, asymmetric envelope. Splitting into neutral –NH₂ and protonated –NH₃⁺ components removed the asymmetry and gave a satisfactory residual.

Table S3. Results of the fitting for XPS data All peaks have been fitted using a Shirley background and a Asymmetric Lorentzian lineshape LA(30) that has been proofed adequate for lightly conductive oxides (22–24).

Edge	Surface	Atom type	Position (eV)	FWHM (eV)	Ratio	Residual STD
O 1s	Clean	Intrinsic	531.0	1.5	0.3	2.3
		Lattice	530.3	1.2	1	
	Adsorption	Intrinsic	531.1	1.2	0.3	1.9
		Carboxylate	532.0	1.4	0.1	
	Oxidation (30 min)	Intrinsic	531.0	1.3	0.35	1.5
		Carboxylate	531.9	1.6	0.1	
Ti 2p	Clean	Ti4+	549.1	1.1	1	3.1
		Ti3+	457.3	1.5	0.05	
	Adsorption	Ti4+	459.1	1.3	1	3.1
		Ti3+	457.3	1.0	0.02	
	Oxidation (30 min)	Ti4+	459.1	1.2	1	3.2
		Ti3+	457.3	1.2	0.02	
C 1s	Adsorption	C-O	289.0	2.1	1	1.0
		C-N	285.9	1.7	1.31	
		C-S	285.2	1.8	1.75	
	Oxidation (5 min)	C-O	288.9	1.8	1	0.2
		C-N	285.8	1.5	1.5	
		C-S/C-Hx	284.8	1.4	2.5	
		C-SOx	286.6	1.8	0.6	
	Oxidation (30 min)	C-O	288.8	2.1	1.0	0.3
		C-N	285.2	1.6	1.7	
		C-S/C-Hx	284.6	1.5	2.5	
		C-SOx	286.5	1.7	1.0	
S 2p _{3/2}	Adsorption	S-H	163.9	1.5	1	1.0
		S-Ti	161.6	1.1	0.4	
	Oxidation (5 min)	S-H	163.9	1.4	1	1.0
		S-Ti	161.7	1.7	0.6	
		S-Ox	166.5	1.1	0.6	
		SO ₃ H	168.7	0.9	0.4	
	Oxidation (30 min)	SO ₃ H	168.7	1.8		0.8
N 1s	Adsorption	NH ₂	400.3	1.5	1	0.5
		NH ₃ ⁺	402.2	1.5	0.6	
	Oxidation (30 min)	NH ₂	400.2	1.8	1	0.7
		NH ₃ ⁺	402.0	2.0	0.53	

S.I. 4 XPS Dark experiment

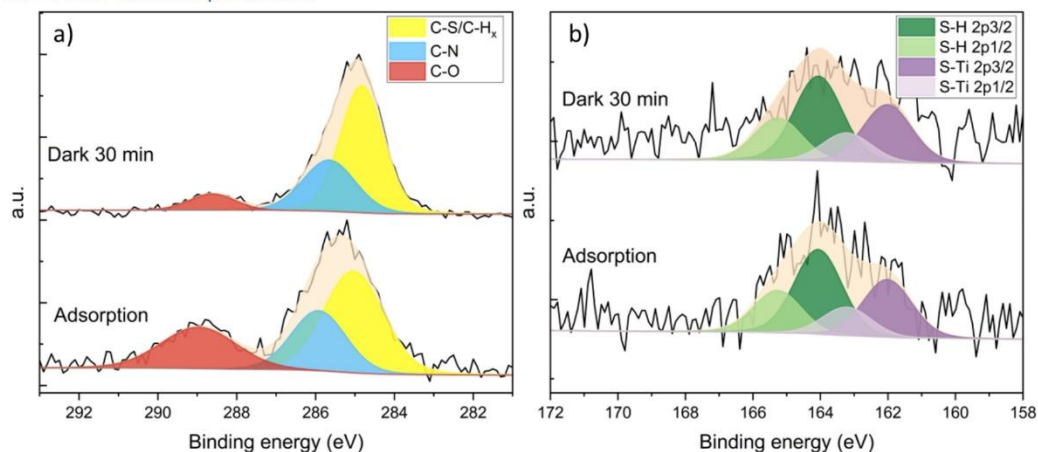


Figure S6. Deconvoluted XP spectra of adsorbed cysteine on anatase $\text{TiO}_2(101)$ under 30 min of atmospheric exposure in dark conditions. Experimental data (black lines) and deconvoluted components (coloured areas) are presented for (a) C 1s, (b) S 2p, before and after exposure at room temperature to atmospheric pressure.

S.I. 5 XPS O 1s after UV

The O 1s spectra recorded before irradiation and after 30 min of UV exposure are shown in Figure S7. No significant spectral changes are observed upon irradiation. The O 1s signal is dominated by lattice oxygen from TiO_2 , which masks the comparatively small contribution from oxygen containing oxidation products. Therefore, the O 1s region does not provide additional insight into the progression of cysteine photooxidation.

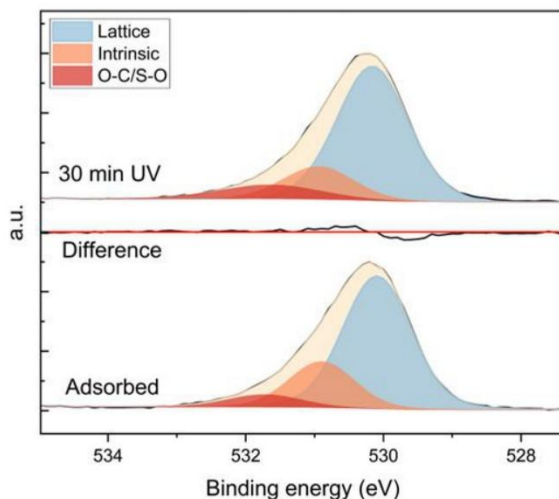


Figure S7. Deconvoluted XP spectra of adsorbed cysteine on anatase $\text{TiO}_2(101)$ under UV irradiation. Experimental data (black lines) and deconvoluted components (colored areas) are presented for O 1s spectra. Difference spectra (30 min UV - adsorbed) illustrate the absence of relevant spectral changes.

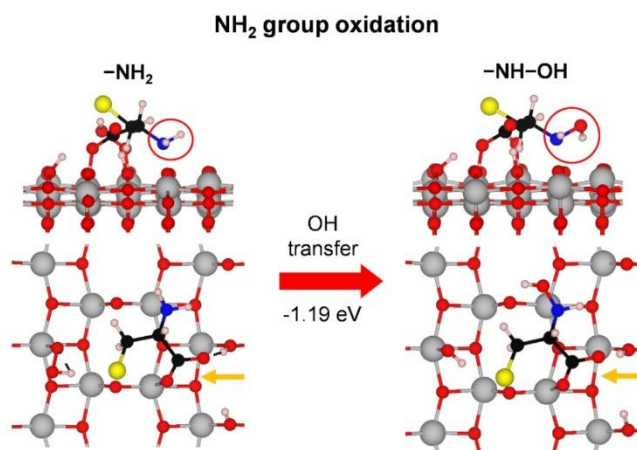


Figure S8. Side and top views of the optimized structures illustrating the reaction pathway in which the -NH_2 group (left) is oxidized to -NH-OH (right) after formation of the superoxo/hydroperoxo intermediate. The structures are calculated using Quantum ESPRESSO with the PBE+D3+U approach. Gray, red, blue, yellow, white, and black spheres represent Ti, O, N, S, H, and C atoms, respectively. For clarity, only a portion of the supercell is shown. The -NH_2 group undergoing oxidation is highlighted with a red circle.

S.I. 5 Calculation of S 2p Shifts Along the Photooxidation Pathway.

To further corroborate the intermediates proposed by the HSE06+D3 reaction pathway calculations, we estimated the relative energetic position of sulphur 2p levels for each intermediate, spanning formal sulphur oxidation states from -2 (thiol) to +4 (sulfonic acid). For these calculations, a localized all electron basis set as implemented in the CRYSTAL17 code was employed. Under these conditions, the pseudo core-hole approach used for the adsorption CLS calculations is not applicable.

Therefore, sulphur 2p level trends were extracted from the projected density of states (PDOS) onto S-derived orbitals for each intermediate. Because all slab calculations were performed with identical settings and referenced to a common vacuum level within the 2D-periodic CRYSTAL17 framework, direct comparison of the relative S derived level positions across intermediates is meaningful. The resulting values and the derived relative shifts are summarized in Table 2 in the main text.

Increased sulphur oxidation stabilizes the S derived electronic levels (shifting them to lower energies in the PDOS representation); when expressed as core-level binding energies relative to a common reference, this corresponds to the experimentally observed shift of the S 2p peak toward higher binding energy with increasing oxidation state.

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Appendix 3: Supplementary Information from Adsorption and Comparison of Asparagine on TiO₂ Polymorphs

Supporting Materials for

Protonation and Binding Configurations of L-Asparagine on Rutile (110) and Anatase (101) TiO₂ Surfaces

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S.I. 1 Clean surface characterization

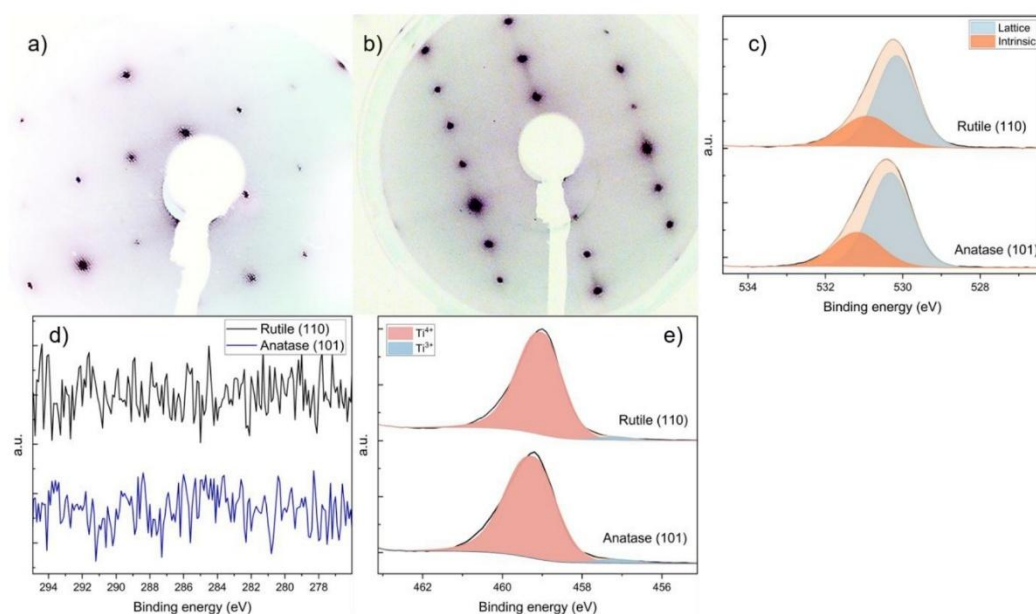


Figure S1. LEED pattern of (a) anatase (101) (b) rutile (110) after preparation under UHV taken at 100 eV. Experimental and deconvoluted XP spectra of the clean rutile (110) and anatase (101) surfaces (c) O 1s, (d) C 1s, (e) Ti 2p 3/2.

S.I. 2 Peak fitting protocol

For each core level, deconvolution started with the minimum set of chemically plausible components; an additional peak was introduced only when demanded by either the envelope shape or the residual trace.

C 1s: L-asparagine has four inequivalent carbon atoms (CONH₂, CH₂, CNH₂, COOH), so four components were fitted. A five peak did not improve the residual and was discarded.

O 1s: On both clean surfaces the line consists of a lattice oxygen peak plus a shoulder from intrinsic defects. Adsorption leaves extra intensity at high binding energy. Adding one component assigns this to carboxylate oxygens and removes the mismatch.

N 1s: A one peak fit produced an overly broad, asymmetric envelope. Splitting into neutral -NH₂ and protonated -NH₃⁺ components removed the asymmetry and gave a satisfactory residual.

Table S5. Results of the fitting for XPS data All peaks have been fitted using a Shirley background and a Gaussian-Lorentzian lineshape GL(30) that has been proved adequate for lightly conductive oxides (1–3). (a) rutile and (b) anatase

A) Edge Rutile (110)	Surface	Atom type	Position (eV)	FWHM (eV)	Ratio
O 1s	Clean	Intrinsic	531.1	1.23	0.4
		Lattice	530.2	1.55	1
	Adsorption	Carboxylate	532.1	1.61	0.13
Ti 2p	Clean	Ti ₄ ⁺	459.1	1.21	1
		Ti ₃ ⁺	457.2	1.07	0.03
	Adsorption	Ti ₄ ⁺	459.1	1.11	1
		Ti ₃ ⁺	457.5	1.16	0.02
C 1s	Adsorption	COO	289.5	1.5	1
		C-NH ₂	286.6	1.9	1.76
		C-H ₂	285.2	1.73	2.06
		CONH ₂	288.8	1.32	1.1
N 1s	Adsorption	NH ₂	400.4	1.78	1.5
		NH ₃ ⁺	401.7	1.55	1

B) Edge Anatase (101)	Surface	Atom type	Position (eV)	FWHM (eV)	Ratio
O 1s	Clean	Intrinsic	531.1	1.27	0.4
		Lattice	530.3	1.45	1
	Adsorption	Carboxylate	532.0	1.45	0.13
Ti 2p	Clean	Ti ₄ ⁺	459.2	1.34	1
		Ti ₃ ⁺	457.1	1.19	0.03
	Adsorption	Ti ₄ ⁺	459.1	1.23	1
		Ti ₃ ⁺	457.2	0.9	0.01
C 1s	Adsorption	COO	289.5	1.35	1
		C-NH ₂	286.5	1.80	3.06
		C-H ₂	285.2	1.42	2.53
		CONH ₂	288.6	1.36	1.1
N 1s	Adsorption	NH ₂	400.3	1.78	2.05
		NH ₃ ⁺	401.5	1.78	1

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