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Rationalization of dye uptake on TiO$_2$ slides for Dye-sensitized Solar Cells by a combined chemometric and structural approach

Valentina Gianotti, Giada Favaro, Luca Bonandini, Luca Palin, Gianluca Croce, Enrico Boccaleri, Emma Artuso, Wouter van Beek, Claudia Barolo and Marco Milanesio

A model photosensitizer (D5) for application in Dye-sensitized Solar Cells has been studied by a combination of X-ray diffraction, theoretical calculations and spectroscopic/chemometric methods. The conformational stability and flexibility of D5 and molecular interactions between adjacent molecules was characterized to obtain the driving forces governing D5 uptake and grafting process, and to infer the most likely arrangement of the molecules on the surface of titanium oxide. A spectroscopic/chemometric approach was then used, yielding information about the correlations between three variables governing the uptake itself: D5 concentration, dispersant (chenodeoxycholic acid, CDCA) concentration and contact time. The obtained regression model shows that large uptakes can be obtained at high D5 concentrations, when CDCA is present and contact time is high, or, in absence of CDCA, only if contact time is shorter, suggesting how to optimize dye uptake and photovoltaic device preparation.

1. Introduction

Photovoltaic (PV) cells based on organic semiconductors and/or organic light harvesters are potentially extremely inexpensive, but their efficiency and stability are still limited when compared to inorganic crystalline solar cells. Among them, Dye-sensitized Solar Cells (DSC) represent a promising and emerging technology.[1] These cells mimic the energy conversion mechanism of photosynthesis, since light is absorbed by an antenna compound (chlorophyll in photosynthesis, a dye in DSC), then an excited electron is produced and captured by a complex system (photo systems I and II in photosynthesis, the form of sugar in photosynthesis and electric current in DSC). The chemical properties of the cell components must be designed and tuned in a careful way to optimize the yield of PV cells. Presently the main issues that still limit their technological applications are: (i) obtaining reasonable (10% for opaque, 5-6% for transparent) conversion efficiency of the DSC modules,[2] (ii) maintaining these yields during the years (~20) needed for a cell working in real conditions, (iii) obtaining reproducible results (± 3-5% differences between modules). To fulfill these objectives, a detailed molecular-level knowledge of the DSC components is of paramount importance.

Even if a great deal of research has been carried out to design more efficient photosensitizers,[4] only recently some efforts have been made in understanding[5,6] modelling[7-10] and controlling[11] of the interactions that play a major role in the dye uptake. Moreover, the dye loading amount can be tuned by changing the bath solvent,[5] which has an important effect on the cell efficiency. Literature data clearly highlighted also the importance of CDCA as co-adsorbent to control dye aggregation and electron injection[12] and to improve performances.[13] However a rationalization of the effect of chemical parameters affecting dye uptake, in relation with chemical forces governing molecular interactions is still lacking. The D5 dye, proposed by Hagberg et al.[14] can be referred as case study for the rationalization of uptake conditions in metal-free dyes. In fact this simple molecule[7,15] can be considered as a model for the widespread class of Donor-π-Acceptor (D-π-A) dyes. This class retains to date the efficiency record for metal-free dyes.[16] In the last decade, various organic functional groups have been combined to generate D-π-A structures. One among the most commonly employed schemes is: the aryl-amine group as electron donor, the thiophene unit as π linker, and the cyanocrylic-acid moiety as the electron acceptor/anchoring group (all of them already present in the D5 molecule).

Structural and crystallographic studies on organic compounds and molecular complexes allow assessing the possible intra- and inter-molecular interactions, which are of paramount importance for the functionality of the materials in working conditions.[15-18] Very few such structural studies can be found in the DSC field because of the complications of dye crystallography, mainly due to the difficulty of obtaining suitable single crystals. Ru-based dye compounds[20] are less difficult to be crystallized and represent the majority among the X-ray crystal structures related to DSC, while only few crystal structures of compounds related to D-π-A sensitizers are available on the CCDC.[21] Relevant structures in the database are: i) a molecule containing the diphenylamino-phenyl and the carboxylic moieties, i.e. a D5 without the vinyl-thiophene linker,[20] and ii) two molecules containing the diphenylamino-phenyl moiety and a thiophene linker.[20] The electronic and molecular surface structure of the functional dye-sensitized interface has also been studied in detail for the D5 molecule by a combination of core level spectroscopy, valence level spectroscopy, x-ray absorption spectroscopy, and resonant photoemission spectroscopy.[22]
In this paper we intend to shed some light on the dye uptake process combining a Design of Experiment (DoE) assisted UV-Vis spectroscopy with a structural investigation. Our aim is to understand the mechanism of dye dispersion and bonding onto the TiO₂ surface, with the long term goal of understanding their influence on the cell macroscopic behaviour. In the present study, the dye related crystallography problems have been overcome by exploiting advanced powder diffraction methods, using different high resolution detectors on a high flux synchrotron radiation X-ray source. We report on the crystal and molecular structure of the polyene-diphenylaniline dye D₅, and two related compounds (4 and 6 in Scheme 1) by powder and single crystal X-ray diffraction respectively. The analysis of their packing features allowed understanding the molecular forces governing their intra- and inter-molecular interactions. However crystallographic studies cannot give direct information on the behavior of D₅ on titania. In order to shed light on the correlations between the main parameters governing the dye uptake, a chemometric-driven UV-Vis spectroscopic study was designed and performed. UV-Vis spectroscopy was used recently by Dell’Orto et al. to assess the kinetics of absorption of the N719 dye onto titania. We choose to exploit a quantitative chemometric approach because it allows maximizing the information content with the least number of experiments. Up to now, the optimization of the experimental conditions of dye uptake was carried out mainly by trial and error or at best by “One Variable At a Time” (OVAT) methods. Only very recently the chemometric approach was proposed in the DSC field by some of us. The present work aims at investigating both the molecular structure and the dye uptake in a synergic way and represents the first part of a larger project we are carrying out with the purpose of understanding, at the molecular level, the mechanisms involved in DSC functioning, with the final aim of improving their yields and stability by optimizing the preparation methods of the cell itself.

2. Results and Discussion

2.1 D₅ synthesis

Syntheses of compounds 4 and D₅ were performed with a slight modification compared to the literature procedures, starting from commercial 4-(N,N-diphenylamino)benzaldehyde 1 (Scheme 1). The first step of our synthetic pathway is a simple Wittig reaction to obtain alkene 2 which was used as a substrate for a subsequent Pd-catalyzed decarbonylative Heck reaction to give intermediate 3. Subsequently, lithiation of 3 with n-butyllithium followed by the addition of DMF yielded the corresponding aldehyde 4. The electron-withdrawing group is inserted in the structure by a Knoevenagel reaction between aldehyde 4 and cyano acetic acid in the presence of piperidine.

D₅ dye was then converted into its corresponding methyl ester (6) to verify the configuration of the 2-cyano-3-(thiophen-2-yl) acrylic moiety. Compound 6 was also obtained, in the same configuration, through the classical Knoevenagel reaction directly from 4.

2.2 Computational study of D₅ conformational flexibility and freedom

The chemical formula of D₅ (Figure 1) suggests that this molecule should be rather rigid and planar, because of the conjugation between aromatic moieties (thiophene and benzene rings) through a C=C double bond. In addition the cyano-acetic group is planar and connected to thiophene by a double bond. The only non rigid part is the three-phenyl-amino moiety, which is non planar with the terminal phenyl groups free to rotate and adopt different conformations. The crystal structures of compounds 4 and 6 from single crystal data gave a clear picture of the stereochemistry around the C=C double bond isomerisation, and confirmed the expected E isomer (see section 2.3). Besides, NMR and chromatography experiments (see ESI, Section 1) confirmed that also in solution only one isomer is present. Conversely, a rather rich conformational variability can arise because of the rotation around the single bonds, as discussed below. A reliable indication about the stable conformation of D₅ in the solid state could in principle be gained from single crystal diffraction data, but the same indication about the dye in solution or when bonded to the titania surface, can only be obtained, lacking direct information, by a combination of experimental X-ray data (section 3.4) and computational analysis by first principle calculations (this section). Having failed all our attempts at growing single crystals of D₅ because of the well known difficulty of crystallizing bulky carboxylic acids, in analogy to what observed for fatty acids, high resolution X-ray powder diffraction (XRPD) was thus used. The limited resolution of XRPD on organic molecules rendered the discrimination between the isomers rather difficult and therefore an accurate conformational analysis was needed.

2.2.1 First principle calculations on stable minima

In the literature, only one isomer of D₅ (named D₅-2a in Table 1) is generally accepted and used. Lacking a single crystal structure of D₅, and being almost impossible to directly and precisely investigate the structure of D₅ onto titania and in
solution during the grafting process, accurate first principle theoretical calculations, combined with an experimental structural study of D5 and parent compounds, have been carried out and reported in detail in a separate paper, together with all strategies and tricks used for structure solution.\cite{34}

In this paper the possible conformational changes were investigated considering the three degrees of freedom (named $\phi_1$, $\phi_2$ and $\phi_3$ and identified in Figure 1), which can assume either the s-cis or the s-trans conformations, being E/Z isomerisation already established. The conformational changes around $\phi_4$, $\phi_5$ and $\phi_6$ are less important because of the symmetry of the phenyl groups. However, for an exhaustive search they were also considered, but only the more stable conformations of D5 and related compounds are reported (see Table SI-2 for detailed geometric features).

![Figure 1: Degrees of freedom of D5 molecule: $\phi_1$, $\phi_2$ and $\phi_3$ refer to O=C-C1=C2, C1=C2-C3=C4 and C5=C6-C7=C8 torsion angles respectively.](image)

Among the possible theoretical conformers, four of them (namely D5-1a, D5-1b, D5-2a and D5-2b) possess stable energy minima below 1.5 Kcal/mol. According to Boltzmann distribution, they are, most probably, the dominant ones for D5 in solution and on the titania surface (i.e. in the relevant cases).

| Table 1. Geometric features using B3LYP functional of the more stable conformers (within 1.5 Kcal mole\(^{-1}\)) after geometric optimizations. |
|---|---|---|---|---|
| $\phi_1$ ($^\circ$) | $\phi_2$ ($^\circ$) | $\phi_3$ ($^\circ$) | [a] | [b] | [c] |
| D5-1a | 0.1 | 180 | 180 | 0.00 | 0.00 |
| D5-1b | 0.0 | 180. | -1.1 | 0.95 | 0.73 |
| D5-2a | 0.0 | 0.1 | 180 | 0.38 | 0.34 |
| D5-2b | 0.0 | 0.1 | -1.8 | 1.29 | 0.98 |
| 4 | ---- | -178 | -177 | ---- | -179 | 4.7 |
| D5 | -9.3 | -173 | -169 | 0.6 | -168 | -175 |
| 6 | -0.9 | 179 | 166 |

[a] 6-31G(d,p); [b] 6-311+G(2d,2p); [c] Molecular structure.

The geometries of the four isomers, after geometric optimization by first principle calculations at the B3LYP/6-31G(d,p) and B3LYP/6-311+G(2d,2p) levels of theory, are depicted in Table 1. 6-31G(d,p) basis set was used to obtain a first fast geometry optimization and screening of possible stable conformations, while 6-311+G(2d,2p) basis set was mandatory to get a careful description of molecular geometries of the conformers and of their relative stabilities. Conformer D5-1a is the most stable and also the most present in X-ray crystal structures (see section below) and thus can be considered the prevalent one at the
equilibrium, The most commonly reported one ($D5$-$2a$)\textsuperscript{14,16} and the other two conformers are less stable by less than 0.5 kcal mol$^{-1}$ and can be present at lower concentrations in solution, according to Boltzmann distribution, and at not equilibrium conditions. It must be noted that, in the case when $D5$ is at first approaching and then linked to the titania surface, the carboxyl group is deprotonated and the conformational degree of freedom around $\phi_1$ becomes irrelevant because the COO$^-$ moiety is symmetric for a 180° rotation. Moreover in the deprotonated $D5$ the energy differences are even smaller (Table 2).

<table>
<thead>
<tr>
<th></th>
<th>$D5$-$1a$</th>
<th>$D5$-$1b$</th>
<th>$D5$-$2a$</th>
<th>$D5$-$2b$</th>
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<td>4</td>
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<td>1.55</td>
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<td></td>
<td>0.00</td>
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<td>0.77</td>
<td>0.31</td>
<td>0.99</td>
</tr>
</tbody>
</table>

[a] 6-31G(d,p), [b] 6-311+G(2d,2p); [c] 6-31G(d,p), [d] 6-311+G(2d,2p); [e] 6-31G(d,p), [f] 6-311+G(2d,2p).

The theoretical calculations suggest therefore that conformers $D5$-$1a$, $D5$-$1b$, $D5$-$2a$ and $D5$-$2b$ are the most probable ones. In fact, three out of these four conformations were experimentally observed in the X-ray crystal structures (see discussion below in the dedicated section), where crystal packing forces play a relevant role in the selection of less stable conformers. The compromise between the intrinsic thermodynamic stability of the isolated conformers and the effect of inter-molecular interactions in the solid-state is well known as observed when comparing theoretical calculations with X-ray structures.\textsuperscript{35} Of course, these conclusions do not take into account the energy barriers for rotation around the C-C bonds, investigated in the next paragraph.

2.2.2 Energy barriers between energy minima as a function of torsion angles

The rotation barriers between the four conformers were explored by Relaxed Potential Energy Scans (R-PES) around the 2 S-C-C=C torsion angles ($\phi_2$ and $\phi_3$). To explore at best this energy surface, with an acceptable computing time, at first two, one-dimensional, R-PES scans were carried out at the same DFT level (B3LYP/6-31G(d,p) and the data are reported in Figure 2a. Then a two-dimensional R-PES at the less demanding HF/3-21G level of calculation was carried out exploring, at the same time, the two torsions thus producing the 3D plot reported in Figure 2b. The basis sets used for geometry optimizations would be too much time consuming and unaffordable for such an extended PES. However HF-3-21G still gave acceptable geometries and energy differences when comparing the energy minima to the results of the more extended basis sets.
The observed minima confirmed at first that the s-cis conformation of D5-1a is favoured and the other three conformers (D5-1b, D5-2a, D5-2b) are the unique stable minima, in agreement with the first principle DFT calculations. The R-PES indicated that rotation around \( \phi_1 \) is easier than around \( \phi_2 \). Moreover there are no other minima and there are no sterically forbidden regions hindering the rotation. The heights of the barrier (about 4 and 10 kcal/mole around \( \phi_2 \) and \( \phi_3 \)) suggest that during D5 manipulation, for both the DoE-assisted uptake experiment here used and, in general, for DSC cell preparation, rotation around this single bond is possible, as also indicated by the fact that compounds 4, D5 and 6 show different conformations in their crystal structures. This conformational flexibility is probably important in driving the D5 uptake on titanium oxide as well as the final arrangement of D5 molecules on its surface. The absolute minimum of the calculations (conformer 1) shows s-trans conformation for both \( \phi_2 \) and \( \phi_3 \) torsion angles, while the conformation usually considered in the literature (conformer 2) shows s-cis and s-trans conformations for \( \phi_2 \) and \( \phi_3 \) respectively. Both conformations are very close in energy and therefore accessible at RT conditions. The larger stability of s-cis conformation suggested by first principle calculations was confirmed by searching distribution of s-cis and s-trans conformation in the structures containing the vinil-thiophenic moiety in CCDC database[34]. This search (Figure SI-4) confirmed a large prevalence of s-trans conformation.

2.3 Crystal structures* of D5, of its precursor (4) and of its methyl ester (6)

The conformational flexibility suggested by first principle calculations had to be confirmed by experimental crystallographic data. From compounds 4 and 6, despite many different attempts, it was not possible to grow a single crystal for D5 and, as explained before, its structure had therefore to be investigated by high resolution synchrotron radiation X-ray powder diffraction. The XRPD study was carried out at ambient conditions, since an experiment at 100K (where better data could be in principle collected) a new phase appeared with formation of a mixture impossible to index. For consistency also compound 4 and 6 were measured at RT. Because of the well known limitations in the accuracy of the structures solved by powder diffraction data, identifying the correct conformations around the \( \phi_1 \), \( \phi_2 \), \( \phi_3 \) torsion angles without a priori information is a rather difficult or even impossible task. In fact the conformations, described in section 3.2 and depicted in Figure 1, have very small electron density differences. Even the high quality of the data recorded with the 1D analyzer detector (BM1B) and the 2D MAR CCD (BM1A) at SNBL did not result sufficient for a successful structure solution, as detailed elsewhere[34]. To overcome the problem, on one hand, high resolution powder diffraction data of excellent spatial and reciprocal space resolution were collected exploiting a Pilatus 2M detector[35] and, on the other hand, data from theoretical calculations and a priori information from the single crystal structures of compounds 4 and 6 were exploited. The crystallization of these two parent compounds resulted much easier and their single crystal structures could give direct and accurate indications about the more stable conformation in the solid state. It is worth noting that both structures 4 and 6 showed that the most stable conformations coincide with the more stable from first principle calculations. This information helped the interpretation of powder diffraction data from D5. At first the single crystal structure of the compound 4, (sect 2.3.1) was solved to determine the torsion angle \( \phi_2 \) and the common geometric features of these compounds, i.e. the planarity of the thiophene group and the geometry of the diphenylamino chromophore. Then, compound 6 (a crystalline derivative of D5) (sect 2.3.1) was prepared to obtain experimental data from XRD single crystal data to shed light on the conformational features of the 2-cyanoacrylic moiety, i.e. on the conformation around the \( \phi_1 \) and \( \phi_2 \) torsion angles. In the following sections the relevant features of the three structures are discussed, while all crystal data are reported in the ESI file.

2.3.1 Single crystal structures of compound 4 and compound 6

Compound 4 crystallizes in the P-1 space group and the asymmetric unit contains two molecules arranged in a parallel fashion along their elongation axis, but rotated by about 90° with respect to the other to form T-like interactions between the aromatic conjugated moieties, as can be seen in Figure 3. The two molecules show two different conformations (s-cis, s-trans) for the \( \phi_2 \) torsion angle (see Table 1), confirming the possibility of more than one stable conformation suggested by theoretical calculations. Conversely \( \phi_3 \) shows an s-trans conformation in both molecules. A short S••••O intra-molecular contact (\( d_{mean}=3.04(8) \) Å) is observed.

Concerning the triphenylamine group, the nitrogen atom is very close to an sp\(^2\) hybridization, since the three C-N-C angles are between 118 and 122° and the torsion angle defining the piramidality of N (i.e. the one obtained by the N itself and the three C atoms bonded to the N), is very close to the 0° value, as expected for a perfect sp\(^2\) hybridization. The two terminal phenyl groups are not co-planar in order to minimize their reciprocal steric hindrance. The remaining part of the molecule is planar with deviations smaller than 4° in all torsion angles, also for \( \phi_1 \) and \( \phi_3 \). Finally hydrophobic inter- and intra-molecular interactions between the phenyl groups of the dibenzylaminic moieties are present.

(a)
Figure 3: Crystal packing of compound 4 (a) and 6 (b) highlighting the hydrophobic clustering of phenyl groups in both cases.

Compound 6 crystallized in the $P2_1/c$ space group with one molecule in the asymmetric unit. The triphenylamine and the thiophene moieties reveal geometries similar to those of compound 4 and also the cyano-acetic group is coplanar with the rest of the molecule. The most relevant information is given by the conformational arrangement around the $\phi_2$ and $\phi_3$ torsion angles, both close to 180° with s-trans conformation within 6° (see Table 1), as in the absolute minimum of first principle calculations. A short $S^{\cdots}N$ intra-molecular contact ($d=3.26(7)$ Å) is observed. The crystal packing of compound 6 is exclusively driven by short contact interactions (less than the sum of van der Waals radii), because no H-bond is possible. Hydrophobic interactions between phenyl moieties are observed, similarly to compound 4. Furthermore the molecular packing also reveals that the short contact network is formed by the intermolecular interaction between the triphenylamine and cyanoacetic groups of adjacent molecules.

2.3.2 D5 structure from X-ray powder diffraction data

The unit cell of D5 can contain four molecules and, given the $P-1$ symmetry with only the inversion centre as symmetry element, two molecules must be present in the asymmetric unit. To solve the structure without biasing the search and exploring at best the structure solution hyper-surface, all four stable isomers D5-1a, D5-1b, D5-2a, D5-2b, were used as starting guess for the real space structure solution of D5, also combining two molecules with different conformations, as observed for compound 4. When the simulated annealing searches are sufficiently extended, in terms of temperature and time, the results converged to a solution with $\phi_2$ close to 0°, while acceptable solutions were obtained with $\phi_3$ close to both 0° and 180°. In other words, two possible correct structure solutions are suggested by simulated annealing. The first has two molecules with conformation D5-1a and small differences in the planarity of the vinyl-thiophene moiety and in the arrangement of the three phenylamino groups, the latter has two different conformations, D5-1a and D5-1b, as observed in compound 4. Conformations D5-2a and D5-2b do not appear in any possible stable solutions among the highly ranked R values. The best fitting of the XRPD data (see figure SI-3 in ESI file) was obtained for the first arrangement with two molecules D5-1a (the absolute minimum of first principle calculations) in the asymmetric unit (see Table 1).

Figure 4: Crystal packing of D5, showing H-bonds and hydrophobic interactions between aromatic groups.

The packing driving forces are head-tail hydrogen-bonds between the COOH moieties of adjacent D5 molecules (Figure 4). Hydrophobic clustering of phenyl groups are observed as in compounds 4 and 6. It can be concluded that the phenyl-phenyl interactions are the common feature of all 3 solved crystal structures and must be very important also when D5 is bound to titania nanoparticles. Apart from these common features, it is surprising that the crystal packing of D5 and its precursor are different. While parallel $\pi-\pi$ stacking interactions are observed in D5, in compound 4 the molecules are pillared in a perpendicular way with T-like interactions (see Table SI-4 in ESI). Compound 6 shows a completely different packing without stacking of planar aromatic moieties, but the phenyl-phenyl are still observed. The torsion angles $\phi_2$ and $\phi_3$ are almost planar (see Table 1) but with deviations, within 10°, larger than those suggested by theoretical calculations (where deviations from 0 and 180° are within 2°, see table SI-4 for a detailed comparison). Such freedom is indeed confirmed by calculated PES, where a
rather flat energy trend is observed between -20 and +20\(^\circ\) and -160 and +160\(^\circ\) in Figure 2a) and by literature experimental data (see figure SI-4 in ESI file). The variety and richness of molecular interactions and deviation from planarity highlighted by crystallographic and computational studies, probably occurring also in solution and after adsorption on TiO\(_2\) surface, uptake suggest that dye uptake is a complex phenomenon requiring a quantitative study for an optimization on both materials use and cell performances.

2.4 Chemometric study of D5 uptake

A Full Factorial Design (FFD)\(^*\) was used taking into account all the parameters involved in the dye uptake in order to maximize the information with the minimum number of experiments to be performed. A Design of Experiment (DoE\(^*\)) approach allows, by carrying only 22 experiments, to evaluate in triplicate the effect of three variables on two series of samples (powder and TiO\(_2\) slides). Instead, with a standard 3D experimental grid, 162 experiments \((3^3\times3\times2)\) would be necessary.

Preliminary experiments with P25 powder were carried out to estimate the correct range of D5 concentrations for the uptake study. Then a first FFD was carried out using different amounts of P25 powder put in contact with D5 solutions at different concentrations with and without the presence of a dispersant molecule (chenodeoxycholic acid, CDCA), in order to evaluate the effects of these parameters in a model system. Finally a FFD experiment applied to a more complex and realistic model on standard TiO\(_2\) slides was carried out, to explore the mutual influence on the D5 uptake in real systems of the three parameters: D5 concentration, CDCA concentration and soaking time (t).

The simplest, fastest and non destructive method for dye uptake evaluation is Uv-Vis spectroscopy, that can indirectly, but precisely measure the amount of dye extracted from the solution by both titania powders and TiO\(_2\) slides.\([36-37]\) The direct evaluation of the amount of grafted dye can be done only by disruptive and more time consuming methods such as Uv-Vis spectroscopy after dye desorption (with the implicit risk of partially degrading the dye) or TGA measurements (less selective and precise and having the drawback of not being applicable to the standard electrodes) on powdered TiO\(_2\) samples. For these reasons, indirect UV-Vis method was selected for extensive FFD studies on real samples (Section 2.4.3), but TGA measurements were also used for validation purposes on some relevant uptake conditions on P25 powders (end of section 3.4.2).

2.4.1 Preliminary evaluations

UV-Vis analyses were performed on D5 ethanol solutions at different concentrations to obtain a mean value of the molar extinction coefficient \((\varepsilon)\) at \(\lambda=448\) nm of 35530 cm\(^{-1}\) mole, since in the literature the only reported value was measured in acetonitrile as solvent.\([39]\) It is worth noting that the maximum number of D5 molecules that can be theoretically grafted must not exceed the physical sorption limit of additional D5 layers not directly bound to titania. To stay below this limit, the suitable amounts of D5 and P25 for the adsorption should range, using 10 ml of D5 solution, from 1.0 to 5.0 \(10^{-4}\) M, when using amounts of P25 ranging from 1.0 to 5.0 mg, respectively. In fact the indirect evaluation of dye uptake by UV-Vis measurements requires that the process consumes a significant (approximately not less than 0.1\%), as estimated from molar extinction coefficient and used concentration of D5 mole fraction of dye. To find the correct ranges of D5 concentrations and P25 amounts the following considerations were made: assuming the chemical formula of TiO\(_2\) (anatase phase, density 4.23 g cm\(^{-3}\)), a spherical shape of the particles with an average diameter of about 20-25 nm (confirmed by Sherrer particle size analysis from grazing incidence XRPD data collected from titania-covered slides as detailed in figure SI-1 in ESI file and it comment), the weight of one sphere of P25 is 3.1906 \(10^{-17}\) g and the surface available for the sorption per mg of P25 results 6.14 \(10^{16}\) nm\(^2\). Moreover as evaluated with MOLDRAW,\([38]\) a molecule of D5 bound to the sphere by the cyanacetic group and with the diphenyl amino moiety, forming the outer part, covers approximately 0.5 nm\(^2\).

The results obtained from this preliminary uptake experiments are reported in Table 3. In each experiment the amount of P25 was put in contact with the D5 solution for 16 hours at 25\(^\circ\)C in a dark bottle in order to preserve the solution from the light. The results are expressed as number of D5 molecules (abbreviated “molec” from now on) retained in batch conditions by 1.0 mg of P25 and the unit is therefore “molec mg\(^{-1}\)”. In the planned experiments the bottom and the top levels of the variation ranges of D5 and P25 (experiments 1-4) were selected; moreover, in order to evaluate the experimental error associated to the method, three replicates were performed with both variables fixed to the values corresponding to the centre of the ranges (experiments 5-7). The evaluated standard deviation associated to the methodology was 4.77 \(10^{-16}\) molec mg\(^{-1}\) and the measured differences in the quantity of grafted D5 are therefore statistically significant.

<p>| Table 3. D5 uptake on P25 powders. |</p>
<table>
<thead>
<tr>
<th>D5 (mM)</th>
<th>P25 (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>6</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>0.3</td>
</tr>
</tbody>
</table>
The obtained data confirmed that the sorption is affected by both variables with a positive correlation (the amount of grafted $D5$ increases as the amounts of both $D5$ and $P25$ increase) and allowed optimizing the experimental procedure. It must be noted that recorded UV-Vis spectra of the $D5$ concentrated solutions show that the wavelength of the absorption maximum has a bathochromic shift of about 20 nm, probably due to the attractive inter-molecular interactions, highlighted by XRD analysis, more likely to occur in concentrated solutions. In order to avoid these aggregation processes, the dispersant CDCA must be included in the real uptake experiments on titania powders (section 3.4.2) and slides (section 3.4.3).

2.4.2 $D5$ sorption on P25 powder

$2^3$ FFD - P25 powder was used as the simplest possible model system. A Full Factorial Design was planned in order to investigate the effect of $D5$ concentration, contact time ($t$) and concentration of the co-absorbent CDCA. In order to investigate the principal and the interaction effects of the three variables a FFD $2^3$ plan was performed and the 8 required experiments (exp. 1-8) are reported in Table 4; moreover three replicates of the central experiment (exp. 9-11) were performed at the beginning, in the middle and at the end of the FFD in order to check the analysis repeatability and to estimate the experimental error.

<table>
<thead>
<tr>
<th>Exp</th>
<th>$D5$ [a]</th>
<th>$t$ [b]</th>
<th>CDCA [c]</th>
<th>Uptake [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>+</td>
<td>0.40</td>
<td>4.0</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-</td>
<td>0.04</td>
<td>28.0</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>-</td>
<td>0.40</td>
<td>28.0</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>+</td>
<td>0.04</td>
<td>4.0</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>+</td>
<td>0.40</td>
<td>4.0</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>+</td>
<td>0.04</td>
<td>28.0</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>+</td>
<td>0.40</td>
<td>28.0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0.22</td>
<td>16.0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0.22</td>
<td>16.0</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0.22</td>
<td>16.0</td>
</tr>
</tbody>
</table>

[a] mM [b] h [c] mM [d] $D5$ molecules mg$^{-1}$ $10^{-6}$

The results reported in Table 4 were used to calculate an Ordinary Least Squares (OLS) regression model relating the experimental result “y”, i.e. the amount of grafted $D5$, to the experimental factors ($D5$ and CDCA concentrations and contact times) and to their interactions. The significant effects were evaluated by a $t$ test where each regression coefficient was compared with the standard error multiplied by the proper $t$ value of 2.92 ($\alpha = 95\%$, 3 degrees of freedom).

The following OLS model was obtained for $D5$ uptake by powdered titania (molec mg$^{-1}$ $10^{16}$), i.e. “$Y_p$" the following equation:

$$ Y_p = 8.11 + 1.69D5 + 1.24t - 1.25CDCA + 1.73D5t $$

which resulted satisfactory since the $R^2$ value was 0.9914 and, as shown in the ESI file (figure SI-5a), the observed and predicted values are in good agreement.

The OLS model indicates the relevant factors and their effects on the amount of adsorbed $D5$: the higher the value of the coefficient in each term, the more important the factor in affecting the response and a “plus” or “minus” sign indicates an increase or a decrease of the $D5$ uptake when the considered factor is increased. All the principal factors are relevant from statistical analysis of experimental data: $D5$ and $t$ are both associated to a positive effect, while on the contrary CDCA has a negative effect, i.e larger CDCA concentrations hamper high uptakes. Nevertheless, for the comprehension of the system, the effects of the interaction factors, when relevant, must be considered. In fact they allow describing the simultaneous effects that the factors exert on the system in either a synergic or in an antagonistic way. In our case only the interaction effect between $D5$ and $t$ is relevant; a graphical method based on a two-way table is the best approach to highlight their mutual interaction.

The two-way table (Figure 5) is built by averaging the response of each couple of combinations with the same values of the two variables: on the rows there are the $D5$ concentration values and on the columns the soaking time values ($t$), so the bottom left quadrant represents the experiments of plan characterized by the lowest $D5$ value (-) and the lowest $t$ value (-); since there are two experiments with these values (i.e. experiments 1 and 5) the average of the responses given by two experiments is reported in the table.
In the bold central cell, moving from left to right corresponds to keeping the D5 concentration constant (and vary the time t from the lowest to the highest value), conversely by moving from bottom to top t remains constant and the D5 concentration increases.

On one hand D5 and t show a synergistic effect, since the largest values of dye uptake were obtained, as expected, when high concentrations of D5 were put in contact for long time (top right corner). In this condition the synergistic effect is dominant also with respect to the CDCA addition, since no relevant variations in the amount of dye uptake were recorded in the experiments with or without the dispersing agent (see experiments 4 and 8 in Table 4). On the other hand both intermediate conditions (long soaking time and low D5 concentration or short soaking time and high D5 concentration) reduce D5 uptake with respect to low D5 concentration and short t (down left corner).

In these experiments the F test\(^{(39)}\) for the presence of the quadratic effect resulted negative, so performing additional experiments to evaluate further variable levels, besides the three chosen ones, would not add any new information about the studied system.

The adopted method can measure precisely, but in an indirect way, the amount of dye extracted from the solution by titania powders and slides. The method was validated by evaluating the quantity of grafted dye also by TGA measurements, which have the advantage of directly detecting the uptaken amounts, but the drawback of being less precise and not applicable to slides used in technological applications.

Thermogravimetric analyses (TGA) - TGA analyses were carried out in air on D5, CDCA and pure TiO\(_2\) powder as reference materials (Figure S1-6a), then on D5-sensitized TiO\(_2\) powders with and without CDCA in the same conditions of the experiments 4 (+ + -) and 6 (+ - +) (Table 2), corresponding to highest uptake in absence and presence of CDCA respectively (Figure S1-6b). Full TGA data plots and comments are available in the ESI file. UV-Vis indirect determination indicated an uptake of 1.0 \(10^{17}\) molecules of D5 for 3.0 mg of P25. Taking into account the molecular weight of D5, this corresponds to an expected weight loss of 2.7%. TGA data indicated for the two analyzed samples a weight loss between 3 and 6%, depending on the adsorption conditions. These values are in agreement with the previous determination (same order of magnitude of the UV-Vis) and confirm that the dye that is left in the solution, precisely detected by UV-Vis measurements, was actually grafted on the TiO\(_2\) powder.

As shown in the ESI file (figure S1-6), the plots of P25 and D5-sensitized P25 are significantly different. A first consideration, confirming a chemical interaction between the dye and the substrate, is the clear difference in the thermal degradation profile shown by pure D5 with respect to the D5-sensitized sample. This suggests that the effect of the contact does not originate a physical mixture, but instead, a system with strong interfacial interactions, able to significantly modify the thermal degradation profile.

While pure P25 shows a total weight loss of 1.4%, with a significant contribution due to physisorbed water desorption, D5-sensitized sample has a lower weight residue due to the decomposition of the organic dye, leading to a final weight loss of 7.4%.

In order to quantify the amount of dye in the sample, a weight loss contribution of P25 similar to the neat material (1.4%) should be assumed and subtract from 7.4% obtaining 6.0%. Since D5 degrade only for the 95.9% of their initial weight the neat weight loss due to D5 can be estimated about of 6.3% of the total weight of the sample.

The estimated value of adsorbed D5 molecules per gram of P25 from these measurements results 9.0\(10^{19}\) Molec gram\(^{-1}\). This result is consistent with the indirect UV-Vis measurements and demonstrates that the main mechanism of dye removal from the contact solution is due to adsorption onto the P25.

In presence of CDCA during the dye uptake, the TGA profile shows an higher weight loss and a slight shift of all the degradation processes at lower temperatures. The onset of the degradation process (appearing above 200°C) is anticipated of about 20°C with respect to D5-P25 system (observed at 220°C), and the maximum of degradation rate is anticipated of about 9°C. Compared with D5-sensitized P25, the additional weight difference (0.68%) suggested the presence of CDCA co-grafted with D5 in the sample. An approximate 1:10 ratio between CDCA and D5 onto TiO\(_2\) surface can be estimated from this experiment.

2.4.3 D5 sorption on TiO\(_2\) commercial slides

After the successful experiment on P25 powders, an analogous FFD 2\(^3\) plan was performed on TiO\(_2\) commercial slides in order to investigate the principal and the interaction effects of the three variables, in the real working conditions. Each experiment consists of a sorption test in which the TiO\(_2\) slides are immersed in 10.0 mL of a solution containing D5 and CDCA at the different concentrations and for the contact times required by the experimental plan. Three replicates of the central experiment (Exp. 9-11) were performed at the beginning, in the middle and at the end of the FFD in order to check the analysis repeatability and to estimate the experimental error. The eight required experiments (exp. 1-8) plus three repetitions of the central point are reported in Table 5, where uptake is expressed, differently from experiments with titania powders, as the number of uptaken molecules in the unit volume of TiO\(_2\) (molec cm\(^{-2}\)). This unit was chosen because is the more direct from the technologic application viewpoint and because is impossible an accurate evaluation of the weight of TiO\(_2\) film on slides. Uptake
values in this unit can be calculated, knowing the thickness of the slides (6.5 ± 0.4 μm), which is homogeneous within this experimental error (see experimental section for details). This homogeneity allows to compare the data from different slides and transform the amount of grafted molecules from molec cm⁻² of slide (the quantity used for technological applications) to molec cm⁻³ of TiO₂ (used in the TiO₂ slide experiments) and molec per weight unit of titania (molec mg⁻¹) used in the powder experiment. It is worth noting that the large apparent differences in table 4 and 5 (3 order of magnitude) is due to the different measurement units.

<table>
<thead>
<tr>
<th>Exp</th>
<th>D5</th>
<th>t</th>
<th>CDCA</th>
<th>t [a]</th>
<th>D5 [b]</th>
<th>CDCA [c]</th>
<th>Uptake [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.0</td>
<td>0.05</td>
<td>0.0</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>24.0</td>
<td>0.05</td>
<td>0.0</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>8.0</td>
<td>0.50</td>
<td>0.0</td>
<td>56.3</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>24.0</td>
<td>0.50</td>
<td>0.0</td>
<td>35.7</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>8.0</td>
<td>0.05</td>
<td>16.0</td>
<td>5.3</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>24.0</td>
<td>0.05</td>
<td>16.0</td>
<td>6.3</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>8.0</td>
<td>0.50</td>
<td>16.0</td>
<td>51.3</td>
</tr>
<tr>
<td>8</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>24.0</td>
<td>0.50</td>
<td>16.0</td>
<td>60.8</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16.0</td>
<td>0.27</td>
<td>8.0</td>
<td>29.1</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16.0</td>
<td>0.27</td>
<td>8.0</td>
<td>28.9</td>
</tr>
<tr>
<td>11</td>
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<td>0</td>
<td>0</td>
<td>16.0</td>
<td>0.27</td>
<td>8.0</td>
<td>29.2</td>
</tr>
</tbody>
</table>

[a] h; [b] mM; [c] mM; [d] D5 molecules cm⁻³ 10¹⁹.

From these results the following OLS model was obtained for D5 uptake by titania slides (Molec cm⁻³ * 10¹⁵), i.e. “Ys” in the following equation:

\[ Ys = 28.2 + 23.1 \cdot D5 + 3.0 \cdot CDCA + 3.96 \cdot t \cdot CDCA + 2.0 \cdot D5 \cdot CDCA + 3.6 \cdot t \cdot D5 \cdot CDCA \]

Eq. 2

which resulted satisfactory (R² = 0.9850); also in this case the observed and predicted values are in good agreement (see ESI, Figure SI-5b).

D5 and CDCA are the only principal relevant factors and are both associated to a positive effect, contrary to titania powder FFD (see q. 1) where CDCA has negative effect. Moreover the interactions of two and three factors are relevant. Also in this case the information contained in the three factor interaction can be efficiently extracted and shown by a graphical method considering the three possible two way tables (see previous section for their detailed definition), constructed using the variation of the experimental response when varying each time a couple of factors, while leaving the third factor constant.

From the data of Figure 6 it is clear that, when D5 concentration is high (see the left part of the figure), it is possible to obtain large D5 uptakes in many different situations (i.e. at low contact time in absence of CDCA, 56.3 molec cm⁻³ 10¹⁵, or even in the presence of high concentration CDCA if the contact time is high, 60.8 molec cm⁻³ 10¹⁵). This behaviour can be explained with the polydispersity of the titania substrate presenting a distribution of adsorption sites. At shorter times and without CDCA, kinetic effects prevail and less stable and more accessible sites are saturated. Conversely at longer times thermodynamic equilibrium is reached, saturating stable sites with a partial bleaching of less stable sites.

When D5 is at low values (see the right part of the Figure 6) the best result was obtained when CDCA and t are high, but the grafted amounts are very small and comparable to the experimental error, so the recorded variations cannot be considered statistically significant; the same considerations can be done about the other two way tables (see Figure SI-7). Also in this case, the evaluation of the second order effect, with the addition of further variable levels to be investigated, was not required since the F-test for the presence of the quadratic effect resulted negative[39].

<table>
<thead>
<tr>
<th>CDCA</th>
<th>D5 uptake (molec cm⁻³ 10¹⁵)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td>51.3</td>
</tr>
<tr>
<td>5.3</td>
<td>6.3</td>
</tr>
</tbody>
</table>
The higher uptake conditions at the most interesting cases of high D5 concentrations can also be clearly seen in Figure 7 visualizing in three dimensions the data of Figure 6.

The different effect of CDCA on TiO2 slides and on TiO2 powder can be explained by the different diffusion conditions and available space for the D5 molecules in the two samples. In fact in the powder sample, the TiO2 nano-particles are suspended in the solvent with no diffusion limitations and are easily accessible to D5. At the same time at concentration of the order of 10^{-4} M, D5 molecules are well diluted and far away one from the other and aggregation effects are limited either in presence or in absence of CDCA. On the contrary on slide samples, when D5 molecules approach the TiO2 slide surface and start penetrating into the interstitial space among the nano-particles of the TiO2 layer, the available space is much smaller, diffusion became a limiting step, with a compromise between kinetic and thermodynamic effects (as discussed before commenting figure 6). D5 molecules are then constrained one close to the others, thus facilitating the formation of dimers and aggregates induced by the interactions unraveled by XRD and calculations. In this situation, the CDCA action as dispersant becomes important to optimize the dye uptake, especially at high concentrations and for long soaking times, both factors able to induce aggregation. Understanding the driving forces of the aggregation processes by structural and molecular interactions analyses was then of paramount importance for the interpretation of the dye uptake results, as summarized in the following section.

3. Discussion on combined approach

The structures obtained from XRD show the most stable conformations suggested by the calculations on the isolated molecules. This implies that the intermolecular interactions dictating crystal packing are not strong enough to vary the thermodynamically stable conformations. Several weak interactions, besides the expected H-bonds, were observed in the three structures, all showing close contacts between the phenyl moieties. The D5 precursor, molecule 4, showed T-like interactions between thiophene groups, while D5 showed parallel packing of the aromatic moieties. These two kinds of stacking are also probable on the TiO2 surface with no definite preference for one of the two arrangements. It can be inferred that the same interactions must play an important role and induce aggregation of D5 related molecules in solution and on the titanium oxide surface. These aggregation forces can explain the well known dispersion problems shown by D5 and by D5 on TiO2 surface, i.e., self absorption and lateral charge transfer between different dye molecules, with reduction of the injection yields.

The information on the energy barriers suggests that preparation and soaking conditions allow the co-existence (in solution and on the surface) of a variety of conformers even different from the most stable ones. Moreover, the electron injection yield during DSC functioning can be in principle conformer-dependent, since the different conformations show different planarity and the electronic conjugation along the D5 framework is modified. A computational study of the excited state structure, taking into account both flexibility and conformational freedom, might provide more insight on the “real world”.

X-ray diffraction and calculations gave interesting indications of the structure of D5 in different situations, but could not evaluate the importance of the disaggregating agent (CDCA) and the influence of time of soaking, concentration of reagents, physical form of titania (powder or slide) on the dye uptake mechanism. The spectroscopy measurements, aided by a chemometric approach to reduce the number of experiments and investigate the interactions between the various parameters influencing dye uptake, allowed answering some of the issues where XRD could not provide insights.

The Full Factorial Design indicated, at first, that titania powder and titania slides behave differently (CDCA role is relevant only in TiO2 slides, see Figure 6), likely due to the larger importance of diffusion problems in the solid sintered thin film. Therefore, among the studied models, the reference one must be the one carried out on TiO2 slides. In this case, time and CDCA concentration are antagonist, meaning that the presence of CDCA allows a large dye uptake only at long soaking times,
while good uptakes can be obtained at low soaking times and no CDCA. These two situations both allow large uptakes, but with long soaking times and with CDCA a uniform titania sparse loading is obtained, as suggested by high injection yields,\textsuperscript{7,14} while with short soaking time and no CDCA D5 aggregation and island formation probably occurs on the titania surface.

4. Conclusions

First principle calculations, X-ray diffraction, UV-Vis spectroscopy, TGA and DoE techniques have been used in a synergetic way to shed light on the destiny of dye molecules before, during and after the grafting process on TiO\textsubscript{2} electrodes. DSC key components, i.e. dye and titania, have been studied from the viewpoints of the molecular structure and of the dye uptake mechanism, using the well-known D5 molecule as a case study. This combined characterization approach provided at first a detailed information about the molecular interactions, stable conformations and flexibility of the dye molecules. R-PES calculations, besides facilitating structure solutions by powder diffraction, suggested that dyes can exploit their conformational flexibility to optimize the grafting and packing on TiO\textsubscript{2} surface, with a wider then expected available conformational landscape. These data are fundamental to better understand, in working conditions, the role of CDCA and the optimized uptake conditions of D5 on a TiO\textsubscript{2} slides. In fact the ability of CDCA in modifying dye uptake (DoE), i.e. that of hindering phenyl-phenyl intermolecular contacts and contrast the T-like and parallel stacking (X-ray), by intercalating on TiO\textsubscript{2} (TGA) between adjacent D5 molecules, is clarified by the quantitatively measuring (UV-Vis) of the parameters involved in dye uptake.

The DoE-assisted spectroscopic investigation was applied to evaluate the dye uptake in DSC. The successful interpretation of the obtained model, carried out by the complementary characterization techniques, allowed us to propose the presented UV-Vis/DoE approach as the simplest, fastest, most reproducible and sensitive method that can be widely applied to understand and optimize the uptake of any kind of dye.

Experimental Section

Materials

TiO\textsubscript{2} (Degussa P25, purity 99.5%) (Germany), ethanol (purity 99.8%) and cheno-deoxcholic acid (CDCA) (>97%) were purchased from Sigma-Aldrich (Sigma-Aldrich Milwaukee, WI, USA). Glass slides covered with TiO\textsubscript{2} were purchased from DyeSol Italia (Roma, Italy). The D5 stock solution was prepared at 5.0 \texttimes\textsuperscript{-4} M by dissolving 0.0445 g in 200.0 mL of ethanol; working solutions at different concentrations were obtained by dilution with ethanol of the stock solution.

Synthesis

Full details on synthesis of compounds 3, 4, D5 and 6 are available in the ESI file section 1.

Instrumentation

1H- and 13C-NMR spectra were recorded on an Avance-200 instrument (Bruker, Milan, Italy) operating at 200 MHz and 50 MHz respectively and ESI-MS spectra were recorded using a LCQ Deca XP plus spectrometer (ThermoElectron Corporation, Rodano, MI, Italy) as detailed in ESI file, section 1. UV-Vis data were collected by a UV-Vis Lambda 900 spectrophotometer (Perkin-Elmer, Monza, MI, Italy). TGA measurements were collected on a TGA/DTA LF1100/851e, equipped with Store Software (Mettler Toledo, Novate Milanese, MI, Italy) instrument, using the following standard conditions: equlibration step at 60°C for 30 minutes, followed by a ramp at 10°C/min rate up to 800°C. Measurements were collected under air flow. X-ray powder diffraction measurements to analyze TiO\textsubscript{2} particle size were performed on a ThermoARL powder diffractometer XTRA and the details are given in the ESI file.

Single-crystal diffraction data were collected using an Oxford Xcalibur CCD area detector diffractometer with graphite monochromator and Mo-Kα (λ =0.71069 Å) radiation. Data reduction and absorption corrections were performed using CrysAlisPRO 171.34.44 (Agilent Technologies, Cernusco, MI, Italy). Single crystal structure solution was performed by direct methods using SIR2011\textsuperscript{40} and refinement with full-matrix least-squares employing SHELX-97.\textsuperscript{41} Hydrogen atoms were generated in calculated positions by SHELX-97. Single crystals of compounds 4 and 6, suitable for X-ray analysis were both obtained by slow cooling of a saturated hot ethanol solution. Attempts at growing D5 crystals from different solvents and different temperature conditions only yielded too small micron-size crystals and powder diffraction experiment had to be performed instead, using the micro-crystals grown in acetoniitrile. Relevant crystal data are reported in the ESI file. X-ray powder diffraction (XRPD) experiments were performed at the ESRF in Grenoble on the BM1A and BM1B beamlines, using a high resolution powder diffraction instrument (used for indexing) and a Pilatus 2M detector\textsuperscript{42} placed at a distance of 120 cm at two different height with respect to incoming X-ray beam to get low and high 2θ angular range (used for structure solution). The Pilatus XRPD patterns were collected using radiation with λ = 0.7040 (1) Å. The calibration was done using the lattice parameters of the NIST Lanthanum Hexaboride (LaB6) standard (SRM 660b; nominal a = 4.15695(6) Å at RT). The crystal structure was solved from powder diffraction data by simulated annealing using the low angle dataset only by EXP02011 software.\textsuperscript{43} The two powder patterns, at low and high 2θ range, were refined together by the Rietveld method using the TOPAS software.\textsuperscript{44} Full details on crystallographic measurements are reported in ESI file.

Theoretical calculations

The structural models of D5 were obtained by first principle DFT calculations employing the G03\textsuperscript{45} software, as detailed in the computational section. A careful analysis of stable energy minima and of the energy barriers separating them was carried out by using the B3LYP\textsuperscript{46} functional and different basis sets depending the size of calculations, as detailed on the result sections.
Determination of D5 uptake

Sorption experiments were carried out by adding, in static conditions, the proper amounts of D5 to the selected amounts of P25 powder for each experiment. The systems were electromagnetically stirred for a total time of 16 hours; then 1.00 mL of the supernatant is collected, centrifuged twice at 26°C, 3000 rpm for 15.0 min, filtered on 0.20 μm polypropylene membrane (VWR International, West Chester, PA, USA). UV-Vis analysis was performed at 447.9 nm for the determination of the amount of dye still present in solution. All solutions were maintained in the dark.

The particle size and film thickness of the transparent TiO2 covered glass (named “TiO2 slides”), purchased by Dyesol, were characterized by XRPD and UV-Vis-NIR spectroscopy respectively, as detailed in Figure SI-1 and SI-2 and their caption. A particle size of about 25 nm and a thickness of the TiO2 film of 6.5±4 μm was detected. These values were used to calculate the amount of available grafting sites and to estimate the amount of D5 that can be adsorbed by a single slide for a better design of the preliminary experimental plan. The TiO2 thickness was checked by NIR measurements (see ESI, Figure SI-2 and Table SI-1 and its comment), analyzing the absorption interference fringes of the TiO2 slides, generated by the similarity of the radiation wavelength and the TiO2 thickness.[14]

The transparent TiO2 slides were immersed, in static conditions in a beaker, in 10.00 mL of the different solutions containing the different amounts of D5 and cheno-deoxycholic acid (CDCA) and for the contact times dictated by the DoE. Concentrations and contact times are usually optimised by trial and error method. Typical literature conditions are 1-0.1 mM for D5, 10 mM for CDCA and 16 h contact time (overnight). Their values were chosen for the DoE to explore the variable space and find the optimal soaking condition.

Then the supernatant was collected, filtered and analyzed by UV-Vis (447.9 nm) for the determination of the amount of dye still present in solution. All the solutions were maintained in the dark.

The P25 powder and TiO2 slides were washed after the sorption experiments by two 10.00 mL aliquots of ethanol; the aliquots were then recovered, centrifuged, filtered and analyzed by UV-Vis in the same conditions of the sorption experiments.

Chemometric analysis

Full Factorial Design, regression models and all graphical representations were performed by Statistica 7.1 (Statsoft Inc., U.S.A.) and Excel 2003 (Microsoft Corporation, U.S.A.).

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The number of molecules removed by the two treatments was similar and about of the same order of magnitude of the estimated standard deviation. To compare the effects of the investigated factors, the levels (usually indicated with + and −) were submitted to the CCDC data centre with submission codes CCDC 953631 CCDC 895123. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

The Design of Experiments (DoE) is based on model systems of different complexity in order to obtain the evaluation and control of the investigated variables in the appropriate variation ranges. In general the exploration of the experimental domain starts with a two level full factorial design (FFD), allowing the study of the effects of the principal factors and of their interactions on the investigated response. The number of experiments required is 2^p, p being the number of investigated factors. These experiments correspond to all the possible combinations of the two levels (usually indicated with + and −) of the considered factors; then, if necessary, other experiments are added in order to study the second order effects of the investigated factors.

In order to verify if the D5 molecules were effectively grafted on the P25 powder, two washing procedures were tested. In the first the P25 powder remaining after the centrifugation in experiments 6 and 7 was contacted with 10.0 mL ethanol and left at rest overnight; then the solution was centrifuged (3000 rpm, 26 °C, 15 min) and the powder was again contacted with 10.0 mL ethanol for 10 minutes; then the solution was centrifuged, added to the previous one and analyzed by UV-Vis. The second method differed only in the contact time of the first ethanol aliquot that was 10 min. The number of molecules removed by the two treatments was similar and about of the same order of magnitude of the estimated standard deviation, indicating that the molecules of D5 are tightly bonded to the surface of titania and not only physisorbed and/or stacked on the surface in weakly bound multilayers.