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Template-stereocontrolled [2 + 2] photoreactions directed by surface recognition on hydrophilic functionalized carbon materials†‡

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Supramolecular assistance of the regioselective synthesis of single dimers from [2 + 2] photoreactions surface-directed by multivalent H-bonding *exo*-templates based on hydrophilic carbon materials (HCMs) is highlighted for the first time. Supramolecular photochemistry of stilbenes assisted by either functionalized carbon nanotubes or sub-microspheres afforded a single *rtct*-isomer after two consecutive steps in solution (UV-irradiation and hydrothermal isomerization). Carbon spheres display the ability to mediate the dimerization of 4-cinammic acid derivatives with moderate to quantitative yields. This result is obtained either in solution or *via* mechanochemical grinding assistance of carbon sphere/cinnamic derivative assemblies. The structure-templating features of such nanomaterials are discussed as a function of surface recognition processes due to the presence of –COOH and –OH groups on the surface and the effective carbon template : substrate ratio.

Introduction

The control of nanomaterials with well-defined shape and size and tunable chemical surface combined with deliberate molecular recognition-directed processes, has emerged as a promising alternative for programmed supramolecular assistance in multi-component nanomaterials engineering.[1] The coupling of supramolecular chemistry with interesting physicochemical properties of nanoarrays (supramolecular nanochemistry) provides new possibilities for the design of better catalysts and selective binding receptors, sensors or templates.[1,2] In this respect, supramolecular assistance to covalent synthesis constitutes a reliable alternative as the catalyst and/or template in the preparation of stereo- and regiocontrolled compounds either in solution or in solid state.[3,4] Particularly, solid state reactions directed by topochemical factors[5] and assisted by auxiliary molecules as templates have been recognised as an interesting supramolecular strategy for the controlled synthesis of single products combined with high yields.[4] In spite of the well-known advantages of these reactions over those in isotropic media, the development of strategies to design photoreactive arrays remains a challenge

for crystal engineers. The difficulty in controlling the organization of the molecules in crystalline assemblies, together with the intrinsic limitations imposed by topochemical principles, does not allow the generalized application of a unique strategy tolerant of structural factors such as the shape, size and chemical group functionality of photoactive molecules.

In the past decades, chemists, inspired by biological systems, have devoted great effort to the tailor-made design of nanocontainers capable of driving stereoselective chemical transformations in their cavities.[3] A number of constrained and organized media have been explored as hydrophobic supramolecular hosts in solution with moderate success either as catalysts or *endo*-templates. This has been achieved by employing confinement and supramolecular interactions to enhance and control the photochemical reactivity and selectivity of different guests in host–guest systems.[3,6,7] Macrocyclic compounds such as cyclodextrins,[8] cavitands,[9] cucurbiturils,[10] hollow coordination cages,[11] crystal liquids[12] and inorganic solids,[13] among others, have been widely used as supramolecular hosts to overcome such limitations. Two recent reviews about supramolecular photochemistry in such systems have been provided by Vallavoju, Sivaguru,[14a] and Ramamurthy.[14b] More recently, strong non-covalent interactions such as cation···π interactions have also been explored as alternatives for the synthesis of head-to-tail dimers from stilbazole derivatives in solution.[15] These approaches play a critical role in improving either the conversion percentage or product distribution and selectivity of the resulting photoproducts. In this sense, efforts have been made in the study of the reactivity of olefins in the solid state based on

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† Dedicated to Dr. Gabriel Chuchani on the occasion of his 59th anniversary in chemical research. Deceased April 30 2017.

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multivalent templates.[16] The present work outlines an opposite alternative that employs divergent *exo*-templates[1a] bearing multiple hydrogen binding sites. Herein, we have envisaged the use of hydrophilic surfaces based on carbon nano and submicro-materials such as functionalized multiwall carbon nanotubes (MWCNT–COOH) and carbon spheres (CS–COOH), which bear –COOH and –OH groups as potential multivalent *exo*-templates to direct [2 + 2] photoreactions either from solution or from solid state. These materials are susceptible to be covalently functionalized and the acid group density of the surface can be modulated by means of functionalization performed post-synthesis[17] or *in situ* during the preparation, which occurs in the hydrothermal carbonization of nano/microspheres from carbohydrates.[18] Such templates can be easily prepared and be effective hydrophilic nanoplatforms for the selective supramolecular recognition of different molecular targets on the surface *via* complementary H-bonding homo- or heterosynthons (*e.g.* carboxyl acids or pyridyl derivatives).[19] Multivalent *exo*-templates might be capable of geometrically positioning the building blocks by templating and self-assembly in close proximity, allowing flexible distances <4.2 Å so that the photoreaction can effectively occur according to Schmidt's criteria.[5] Therefore, subsequent reactions on the preassembled supramolecular array can be deliberately performed on the surface and the covalent product can be easily removed from the surface by simple acid–base control. Besides, such interactions might modify the photophysical and photochemical properties of the substrate. In this contribution, we report the first examples of HCMs as multivalent H-bonding templates to control [2 + 2] photoreactions in solution. The potential of these templates is evaluated in the supramolecular photochemistry of pyridyl or carboxylic compounds to yield a single dimer. In particular, the ability of CS–COOH to template different olefins, such as bis(pyridyl)ethylenes and cinnamic derivatives, either in aqueous solution or in the solid state, is assessed.

Results and discussion

Carbon material preparation and characterization

In previous studies on the synthesis and characterization of new composites bearing polyoxometalates (POMs),[20] an alternative route was found to generate hydrophilic groups based on oxygenated groups such as carboxylic, epoxide, hydroxyl, quinone or other carbonyl functional groups *via* chemical oxidation under mild conditions, using POMs with H_2O_2. This process is greener than those involving the use of strong and hazardous oxidants such as inorganic acids, bases and chlorates, among others.[17] In this case, functionalization of pristine MWCNTs or CSs was carried out *via* oxidation with $H_3PW_{12}O_{40}$ and H_2O_2 under hydrothermal conditions at 180 °C for 24 h. The chemical changes to the surface were evaluated by FT-IR spectroscopy and point of zero charge (pzc) determination. The pzc values were acidic for both MWCNT–COOH and CS–COOH (3.84 and 1.87, respectively). Since the pzc value is directly proportional to the superficial pH

(pHpzc), which defines the ionizing or ion exchange capacity, it is evident that the carbon spheres have a higher surface amount of COOH groups than MWCNT–COOH. FT-IR also revealed the presence of absorption bands related to the presence of carboxylic and –OH groups (see ESI,‡ Fig. S1–S3). These observations confirm the presence of surface hydrophilic groups capable of interacting with complementary chemical groups *via* the formation of supramolecular synthons. Typical SEM images of MWCNT–COOH and CS–COOH prepared with the addition of a POM are shown in Fig. S1 and S2.‡

Photochemistry in solution

Symmetric stilbenes such as *trans*-1,2-bis(*n*-pyridyl)ethylene (where *n* = 2 or 4; 2,2′-bpe or 4,4′-bpe) were used as initial targets in order to evaluate the effect of both HCMs as *exo*-templates. MWCNT–COOH or CS–COOH in a water/ethanol-dispersion was mixed with a solution of stilbenes in H_2O/ethanol, with a HCM/stilbene ratio of 1:3. The mixtures were kept under magnetic agitation overnight to ensure surface/molecule interaction and after, these dispersions were irradiated at 302 nm for 48 h. After the irradiation, the products were extracted with $CHCl_3$ and characterized by ^{1}H-NMR spectroscopy (Fig. S4–S7‡). The corresponding spectra show the formation of a mixture of dimers as unique products (*rctt*-, *rtct*- and *rcct*-isomers) with a high to moderate conversion of the dimerization reaction (100% and 72% for 2,2′-bpe and 4,4′-bpe, respectively). In both cases the *rctt*-dimer was the major product (Fig. 1 and Table 1).[10a,21] Neither the *cis*-isomer nor its by-products were observed in these photoreactions in any case when CS–COOH was used as the template, in contrast to similar works reported in solution.[21a] This result suggests the anchoring of the molecules on the surface *via* supramolecular heterosynthon interactions with the chemical groups available, thus avoiding the process of *cis*–*trans* isomerisation and the formation of additional by-products. Similar results were obtained using MWCNT–COOH as the template, but the conversion yields of both reactions were lower than those obtained with CS–COOH (73% and 64% for 2,2′-bpe and 4,4′-bpe, respectively). Such a
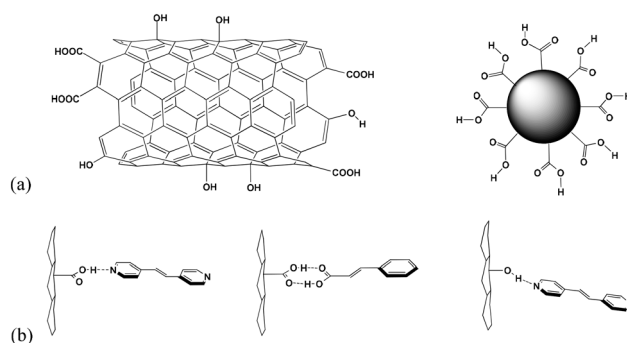

Fig. 1 (a) Schematic representation of functionalized carbon nanotubes (MWCNT–COOH) and carbon spheres (CS–COOH). (b) Possible supramolecular interactions between the surface and olefins.

Table 1 Product distribution[a] (%) upon irradiation of *trans*-1,2-bis(*n*-pyridyl)ethylenes in solution

Products (%)					
Medium[b]	% conv.	1	2	3	4
CS–COOH					
2,2′-bpe	100	—	74	4	22
4,4′-bpe/	72	28	51	11	10
MWCNT–COOH					
2,2′-bpe/	82	18	62	11	9
4,4′-bpe/	64	36	43	15	6
Isomerisation under HC 150 °C[c]					
CS–COOH					
2,2′-bpe	100		—	100	—
4,4′-bpe	88		—	100	—
MWCNT–COOH					
2,2′-bpe	82		—	100	—
4,4′-bpe	64		—	100	—

[a] The percentage of conversion (%) was calculated based on integration of ^{1}H NMR signals. [b] Photochemistry assisted by HCMs in solution. [c] Isomerisation assisted under hydrothermal conditions. Quantitative conversion into the *rtct*-isomer is based on initial relative yield from the mixture of isomers.

difference might be associated with the lower density of surface acid groups on the MWCNT–COOH as compared to that on the spheres, in agreement with the pHpzc values reported above. In further photoreactions with stilbenes, the resulting mixture was heated under hydrothermal conditions at 150 °C for 2 days. The extraction with CHCl₃ and re-crystallization revealed the regioselective and quantitative isomerisation of the *rctt*- and *rcct*-isomers to the most stable *rtct*-isomer for both stilbenes (Fig. 2 and S9†). This isomerisation process is self-catalyzed by the presence of acid groups on the template in both cases[22] (Fig. 3). The combination of supramolecular photochemistry in solution with the isomerisation assisted by HCMs under hydrothermal conditions provides a novel and reliable synthetic route for the regioselective synthesis of a single isomer from two sequential steps in solution.

The above results prompted us to evaluate the general applicability of MWCNT–COOH and CS–COOH as templates in photoreactions of other olefins with different functional groups and substituents. Twelve asymmetric olefins based on cinnamic acid derivatives were tested. The photochemical behaviour of these compounds has been widely explored both in solution and in solid state.[23,24] It is well-known that such molecules do not dimerise in solution, and only the *cis–trans* isomerisation process is observed. Similar irradiations of cinnamic and 4-Cl–cinnamic acids were first carried out using MWCNT–COOH or CS–COOH. Surprisingly, the preliminary characterization by ^{1}H NMR of the extracted solids with CHCl₃ after the irradiation revealed that the dimerization took place cleanly on the hydrophilic surface when CS–COOH was used as the template. This suggests that CS–COOH can be used for the regioselective formation of a single isomer with a quantitative yield from cinnamic derivatives in solution (Fig. S10 and S11‡). Other 4-cinnamic derivatives such as **5f**: 4-Br– and **5h**: 4-CF₃–cinnamic acid showed moderate yield (Table 2, Fig. S12–S21‡), which is in contrast with the formation of the mixture of dimers found during the stilbene photoreactions. In some cases such dimers were obtained in moderate to quantitative yield. On the other hand, low conversion to the photodimer was obtained when MWCNT–
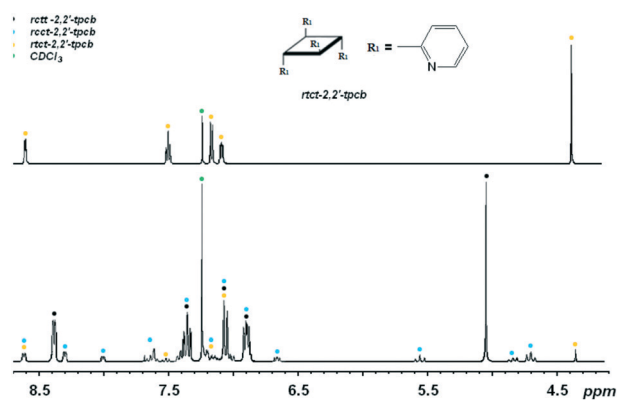

Fig. 2 Comparative ^{1}H-NMR spectra in CDCl₃, showing the quantitative conversion of the mixture of photodimers obtained from the irradiation in solution (*rctt*-, *rcct*- and *rtct*-2,2′-tpcb isomers) (bottom) into the *rtct*-isomer by heating under hydrothermal conditions in the presence of CS–COOH (top).
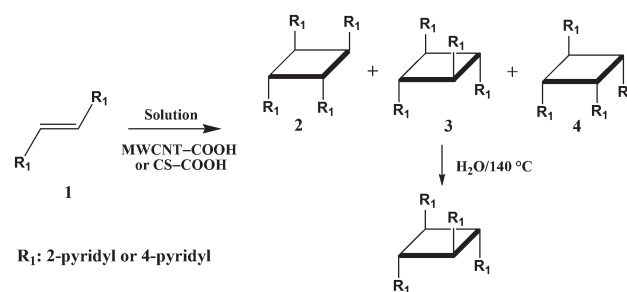

Fig. 3 Photodimerization of stilbenes in the presence of MWCNT–COOH or CS–COOH and isomerization of the stereoisomer mixture to the thermodynamically more stable *rtct*-isomer.

Table 2 Product distribution (%) upon irradiation of *trans*-cinnamic acid derivatives either in solution or in the solid state (runs 1–3). Photoproducts identified: α-truxillic (**6**) or β-truxinic (**8**)/*cis*-isomer (**7**)

Cinnamic derivatives	Solution product^a 6 : 8/7		Run 1 6 : 8/7		Solid state run 2 6 : 8/7		Run 3 6 : 8/7	
5a	100	—	100	—	100	—	100	—
5b	—	—	—	—	—	48/3	—	90/4
5c	—	100	—	100	—	100	—	—
5d	—	—	—	—	—	—	—	—
5e	—	—	—	—	—	—	—	—
5f	—	33	—	8	—	52	—	85
5g	49	—	—	—	69	—	93	—
5h	—	—	—	7	—	80	—	95
5i	—	—	—	—	—	—	—	—
5j	—	—	—	—	—	—	—	—
5k	—	—	—	—	—	—	—	—
5l	—	10/8	—	—	—	25	—	80/7

^a The conversion percentages (%) were calculated based on integration of ^{1}H-NMR signals corresponding to the photoproducts: α-truxillic (**6**) or β-truxinic (**8**)/*cis*-isomer (**7**). Run 1: Photochemistry in the solid state from direct mechanochemical self-assembly of CS–COOH/olefin. Run 2: Photochemistry in the solid state of impregnated and dried CS–COOH with an excess of olefin in a mass ratio of 1 : 20. Run 3: Photochemistry of impregnated and irradiated CS–COOH/olefin mixtures combined with two additional grinding–irradiation cycles.

COOH was used as the template with cinnamic acid in solution. In this case the percentage yield of the dimer ranged from very low to moderate (<30%), depending on the MWCNT–COOH/cinnamic acid ratio (Fig. S22‡). These results may be also attributed to the lower concentration of surface acid groups on the MWCNT–COOH, as compared to that found on the spheres.

In order to ascertain the effect of the template functionalization degree on the photoreaction, a new assay was conducted using pristine MWCNTs as a template model, given their hydrophobic nature (MWCNT-blank). Irradiation of cinnamic acid using MWCNT-blank in an ethanol-dispersion was performed under the same conditions in a mass ratio of 1 : 3. Interestingly, no dimerisation occurred after 48 h of irradiation. In contrast to the results obtained with functionalized carbon templates, the ^{1}H NMR spectrum of the extract resulted in a 67% conversion to the *cis*-isomer as the unique product. This conversion is higher than that obtained in solution in other reports.[10,23] Apparently, the lack of hydrogen anchoring sites on MWCNT-blank and the extended π–surface and π–π interactions between the template and substrate favour the stabilisation of the *cis*-isomer rather than the photodimerisation reaction. These results strongly suggest that the adsorption of the different substrates directed by supramolecular hydrogen bonding interactions plays a fundamental role in the control of the resulting photoproducts by preventing the process of geometrical isomerisation and the formation of additional by-products.

A surprising result was that 2- or 3-substituted cinnamic derivatives such as 2-Cl– or 3-Cl– **e** and 4-substituted ones such as **5i**: 4-NO₂–, **5j**: 4-CH₃O–, and **5k**: 4-OH– (see Table 2) were photoinert upon irradiation using CS–COOH as the template (Fig. S12–S21‡). On the other hand, in every case, the regioselective formation of a single dimer-type was observed, which was identified to be either an α-truxillic- or β-truxinic-isomer (α-dimer: *rctt*-head-to-tail and β-dimer: *rctt*-head-to-

head configurations, respectively) based on the shift of the signals in the ^{1}H NMR and the coupling constant of the photoproducts together with the determination of their melting points.[23,24] The formation of an α-truxillic-isomer was favoured when the substituents were hydrophobic groups (Fig. S10 and S14‡), while 4-halogen-substituted cinnamic derivatives afforded exclusively the formation of a β-truxinic-isomer (Fig. 4). These results are in sharp contrast with those of common photodimerization of these molecules into hydrophobic *endo*-templates.[24c]

Both the nature of the substituents and the substitution at positions 2- and 3- on the aryl ring may significantly affect the relative orientation of the molecules on the surface. This could be a consequence of possible secondary supramolecular cooperative interactions with the substituents, whether on the surface or by solvation effects. Multivalent interactions are stronger than the equivalent monovalent ones and may lead to a greater and more stable affinity with the surface, preventing the molecules from being oriented in favourable photoreactive pairs. These results suggest that the reaction occurs between pairs adsorbed on the surface, probably
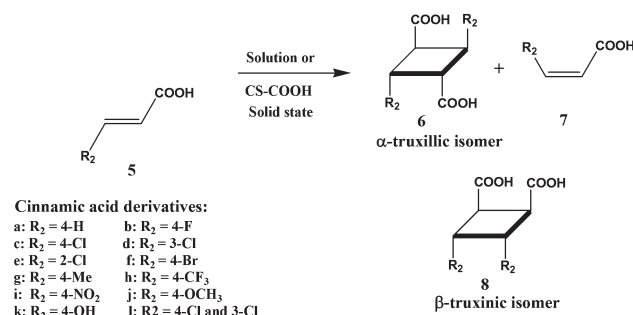
Fig. 4 Photodimerization of cinnamic acid derivatives in the presence of CS–COOH in solution and/or in the solid state *via* mechanochemical-assisted self-assembly.

assisted by the formation of homosynthons between the acid groups on the surface and the cinnamic derivatives. This remarkable feature of the obtained dimer also suggests that CS–COOH acts as an effective *exo*-template.

Mechanochemical self-assembly and photochemistry in the solid state

To gain information about the photoreactivity on the spheres, a new set of reactions were evaluated in the solid state. Liquid-assisted mechanical co-grinding[25] of CS–COOH and the respective photoactive olefin in solution was performed for 30 min with some drops of ethanol (Fig. 5). The resulting mixtures were irradiated using the same wavelength and irradiation time. The characterization by ^{1}H NMR of the extracted solids revealed that the dimerization also occurred in several 4-cinnamic derivatives in the absence of the solvent (**5a**: 4-H–, **5c**: 4-Cl–, **5f**: 4-Br–, and **5h**: 4-CF$_3$–). However, the yield of the photoreactions was lower or zero as compared to the same reactions in solution, except for **5a**: cinnamic and **5c**: 4-Cl–cinnamic acid, wherein it was quantitative for both compounds. These results confirm our hypothesis that the photoreactivity is favoured by the presence of hydrophilic groups on the surface. The stilbenes were also photoinert, suggesting that the interaction of the stilbenes with the surface may occur in a dynamic way in solution, probably due to the presence of different interactions, such as in carboxylic–pyridine and/or –OH···pyridine heterosynthons, among others.[4c,d] This could explain the formation of a mixture of dimers characteristic of the photoreaction in solution of these compounds, in contrast to that observed for cinnamic derivatives.

The yield of the product in these reactions is very sensitive to the carbon material/olefin ratio. Initial optimization was carried out for three CS–COOH/olefin mass ratios (30:50, 30:100 and 30:150), with the best conversion obtained for 30:100. These preliminary observations can be interpreted as a function of the adsorption of the molecules and the density of the location and preorientation of the substrate on the surface. Thus, a plausible explanation for the observed sensitivity may be that the yield significantly depends on the substrate loading. At low loading, there is a small probability that the molecules are adsorbed on the surface by pairs in close proximity, which decreases the possibility of favourable intermolecular contact for the photoreaction to occur. On the other hand, at high loading the molecules adsorbed on the surface can react. However, the molecules remaining in solution can affect the relative orientation of adsorbed molecules due to potential hydrophobic interactions between these two groups of molecules, reducing the yield of the reaction. Likewise, it is possible that geometrical photoisomerization is also favoured. It was therefore hypothesized that complete surface saturation by the substrate is the ideal condition, giving the maximum surface coverage of CS–COOH. For such cases the yield of the reaction should be close to quantitative conversion (Fig. 5).

To test this hypothesis, a new set of solid state reactions with photoactive 4-cinnamic molecules were performed. An excess of substrate was used in relation to the template in solution (600 mg of olefin and 30 mg of CS–COOH). The mixtures were maintained overnight under magnetic agitation to ensure their interaction, and then centrifuged to separate the loaded CS–COOH. The excess liquid was separated by decantation. Mass balance between the amount added in excess during the impregnation and the residue recovered from the solution after centrifugation revealed a variable quantity of the adsorbed amount in grams, depending on the substrate studied. However, the normalized values by molecular weight and amount of carbon spheres (g) tended to an average of approximately *ca.* 70 mmol g^{-1}. This appears to be the surface coverage saturation value, except for cinnamic acid, which was much lower (33 mmol g^{-1}). These results are consistent with the proposed model (Fig. 5). The impregnated spheres were dried and irradiated for 48 h and then split into two portions. The first portion was treated with CHCl$_3$ and a small amount of DMSO to isolate the products of the reaction in the solid state, and characterized by ^{1}H-NMR spectroscopy. The yield obtained was always higher than that in similar reactions in solution or by direct mechanochemical self-assembly (Table 2, run 2). It is noteworthy that **5b**: 4-F–cinnamic acid was only reactive under these conditions, which indicates that this approach can be also used for the study of supramolecular catalysts in the solid state.[27]

Taking advantage of previous studies on mechanochemistry to improve the yield of any photoreaction *via* multiple grinding–irradiation cycles, we applied two additional grinding–irradiation cycles to the second portion.[26] These mixtures were mechanically re-ground for 15–30 min with some drops of ethanol and again irradiated at the same wavelength and irradiation period. The characterization by
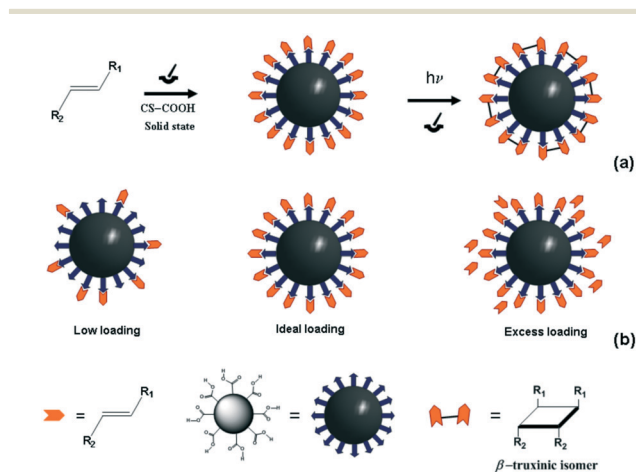

Fig. 5 (a) Cartoon representation of the self-assembly *via* mechanochemistry and the combination of irradiation and grinding cycles in order to improve the yield of the [2 + 2] photoreactions in the solid state, showing the possibility to obtain a β-isomer. (b) Different possibilities of the amount of substrate loaded on a carbon sphere directed by surface recognition, depending on the CS–COOH/olefin mass ratio used.

^{1}H-NMR of the extracted solids revealed that the yield of the products was always higher than the first set of reactions with one single irradiation cycle (Table 2, run 3), which led to a remarkable improvement in the reaction yield with high conversion values for some cases (for example, 48–90%, 52–85% and 25–80% for **5b**: 4-F–, **5f**: 4-Br– and **5l**: 3,4-dichlorocinnamic derivatives, respectively). In contrast, the 2-, 3- or 4-derivatives such as **5d**: 3-Cl–, **5e**: 2-Cl–, **5i**: 4-O$_2$N–, **5j**: 4-CH$_3$O–, and **5k**: 4-OH–cinnamic acids were photoinert under all of the experimental conditions studied. A representative example of the photoreactivity of one of the cinnamic derivatives under the different experimental conditions above described is shown in Fig. 6. These results suggest the concomitant disassembly of the photoproduct from the surface followed by recombination of unreactive molecules into new pairs on the anchored groups available on the surface. Thus, a mechanochemically assisted re-assembly occurs that enables the reactivity of the remaining unsaturated molecules.

At the present stage and based on the above observations, some explanations can be put forward for the intriguing regioselective formation of single α- or β-isomers. The obtaining of such isomers can be speculated to have occurred by three different ways of substrate adsorption on the surface: a) perpendicular to the surface *via* hydrogen homosynthons between acid–acid groups. In this case, π–π interdigitation might occur between adsorbed molecules on neighbouring carbon spheres[2c] (Fig. 7(a)); b) simple absorption by surface saturation of a single sphere due to substrate excess. These two adsorption modes could lead to the formation of head-to-tail photodimers. This configuration would be especially favourable for the derivatives bearing hydrophobic or steric substituents; and c) edgewise or flat adsorption of cinnamic molecules on the surface. In this case, multiple interactions such as H-bonding, π···π and halogen···halogen,
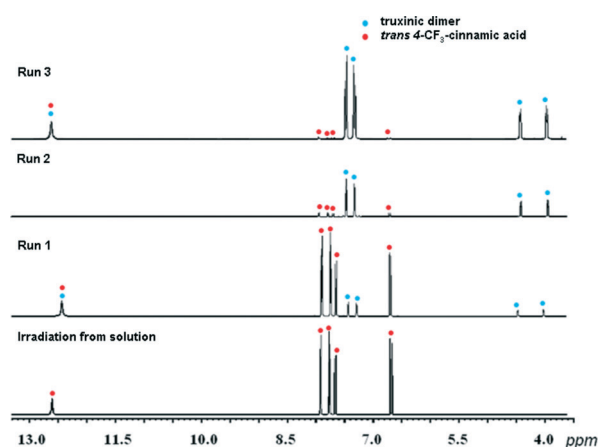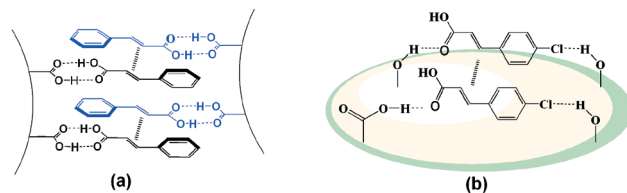

Fig. 7 Possible supramolecular interactions directed by H-bonding interactions between hydrophilic groups on the surfaces: a) stacking head-to-tail *via* π–π interdigitalization between adsorbed molecules on different spheres. b) Lateral adsorption of molecules on the surface.

and stacking of adjacent molecules in a head-to-head manner can generate the necessary geometrical conditions for dimerization. In particular, halogen···halogen contacts are attractive interactions well-known for favouring the molecular stacking into β-arrangements in the solid state[28] (Fig. 7(b)). In the three absorption ways, contacts can be easily regenerated *via* mechanochemical assistance in the solid state, which accounts for the yield improvement in all cases.

On the other hand, to provide some direct evidence of the preferential adsorption and interaction sites on carbon sphere templates, SEM analysis of saturated CS–COOH with **5a**: cinnamic acid was performed. The image shows that the molecules are homogenously distributed on the surface of the spheres, with no formation of segregated crystals or powder (Fig. 8). Additionally, the FT-IR spectrum of these spheres shows the absorption bands corresponding to the overlapping of both components (CS–COOH/cinnamic acid). These results provide strong evidence that supports the full coverage of CS–COOH by unsaturated molecules (Fig. S22‡). Likewise, some FT-IR band shifts are observed when impregnating the carbon spheres with the olefins. In particular, the absorption band corresponding to C=O groups associated to the carboxylic groups of cinnamic derivatives on the surface exhibits a shift in the range of 10–12 cm^{-1} in comparison to free cinnamic derivatives. This suggests an additional
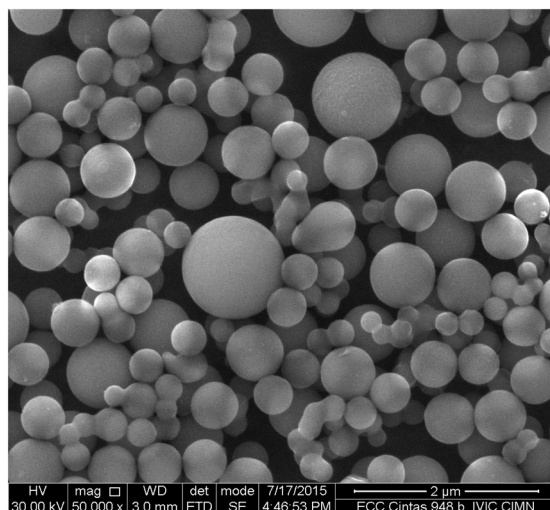

Fig. 6 Representative ^{1}H NMR spectra of a cinnamic derivative (**5h**: 4-CF$_3$–) in solution (bottom) and the solid state reactivity under different experimental conditions (run 1: irradiation in the solid state from mechanochemical self-assembly. Run 2: Irradiation of impregnated CS–COOH with an excess of olefin in the solid state. Run 3: Impregnation–irradiation in the solid state + two additional grinding–irradiation cycles).

Fig. 8 SEM image of impregnated CS–COOH with cinnamic acid.

property of these spheres that make them potential adsorbents for preferential sequestering of carboxylic acid molecules from solution.

Conclusions

In summary, we have here reported the unprecedented ability of HCMs as *exo*-templates to direct stereocontrolled [2 + 2] photoreactions *via* surface recognition of different types of olefins either in solution or in the solid state. The combination of supramolecular photochemistry assisted by HCMs in solution with hydrothermal isomerisation can efficiently be used for the regioselective synthesis of single *rtct*-dimers from stilbenes *via* two sequential steps in solution. On the other hand, CS–COOH spheres can efficiently drive the dimerization of 4-cinammic acid derivatives to afford single α- or β-dimers. The combination of self-assembly with sequential grinding–UV irradiation cycles provides an efficient route to obtain single dimers with high to quantitative yields in the solid state. Both HCMs constitute new multivalent H-bonding templates which can be easily prepared and may emerge as novel alternative *exo*-templates *versus* *endo*-templates. Thus, supramolecular nanochemistry opens up endless opportunities for designing a new class of multivalent nanotemplates capable of favouring the regioselective preparation and/or improving the yield of new and conventional cyclobutane-like derivatives, which are difficult to access in the liquid phase or by established solid state protocols. This supramolecular approach can be very helpful to overcome the limitations imposed by the topochemical postulates in the regioselective obtention of dimers from crystalline assemblies. Additionally, this alternative provides an efficient green route to scale these reactions to gram quantities. The widespread potential use of HCMs and other functionalized surfaces as templates is currently being explored for the dimerization of other stilbenes, stilbazoles and unsaturated acids. Likewise, the optimization of the HCMs/olefin mass ratio remains under investigation in order to evaluate the efficiency of HCM templates in solution.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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