Continuous Flow Photo-oxidations Using Supported Photocatalysts on Silica

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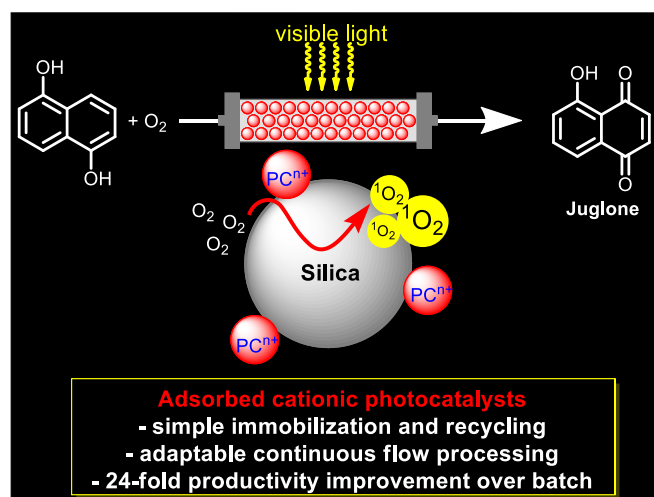
ABSTRACT: The immobilization of soluble photocatalysts, or photosensitizers, has the potential to reduce the environmental footprint as well as the costs associated with visible-light photochemical processes. We report here on the straightforward preparation of non-covalently supported photocatalysts on silica using electrostatic interactions and compare the activities of these new photocatalytic systems in the photo-oxidation of 1,5-dihydroxynaphtalene to juglone in batch and in a fixed bed flow reactor. This study demonstrates that simple immobilization strategies can produce stable heterogeneous photocatalysts and provide promising processing options with an up to 24-fold improvement in productivity in flow compared to batch.

KEYWORDS: Visible-light photochemistry, Photo-oxidation, Singlet oxygen, Heterogenized catalysts, Flow chemistry, Juglone.
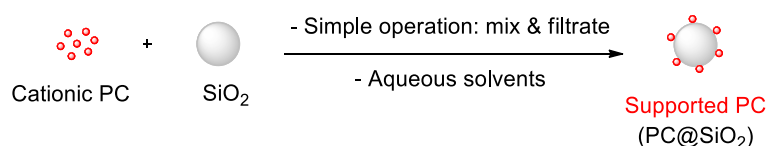
INTRODUCTION

Visible-light photocatalysis has recently witnessed a huge development in organic synthesis as it enables powerful transformations and efficiently complements ultraviolet-light (UV) photochemistry.[1] This technology is attractive from a sustainability standpoint because photocatalysis can induce very selective reactions and visible-light is less energy demanding than UV light.[2] However, visible-light photocatalysis requires the addition of catalytic amounts of soluble dyes (photocatalysts (PC) or photosensitizers) which are difficult to recover after the reaction.[3] This can generate important sustainability and costs issues, especially in the case of organometallic PCs which are made of expensive rare-earth transition metals.[4] Therefore, ingenious recycling strategies have been recently developed, such as supporting these chemicals on solid materials to allow simple reuse and limit time consuming and/or costly purifications.[5] Some of these recycling options have also been successfully demonstrated in flow reactors, where continuous catalyst separation can be carried out either downstream or in a single operation using fixed-bed reactors.[5d, 6d,e] The latter is very attractive because it allows to generate a localized excess of catalyst by circulating the substrate over a packed catalytic bed, thereby promoting faster conversions, but it is also challenging in the case of photochemistry, because light has to efficiently penetrate in the reactor.[7] This approach has been successfully exploited in the field of continuous hydrogenation reactions, however, it has so far found little application in photochemical manufacturing with visible-light.[7,8] An early example was reported by Carofiglio and Maggini who used a covalently linked fullerene photosensitizer on silica or polystyrene beads hosted in microstructured photoreactors.[7a] More recently, Poliakoff and George used a porphyrin immobilized by acid base interaction on a sulfonated resin in
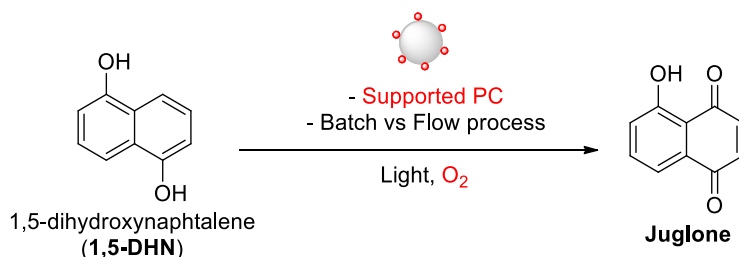
scCO$_2$ to produce the antimalarial drug artemisinin.[6e] Belecki and Gupton reported on the production of the same target using rose bengal covalently linked to a Merrifield resin in a packed bed photoreactor.[7b] The same PC was used in a more recent work by Monbaliu and Heinrichs but as covalently linked to mesoporous silica nanoparticles. The system was efficiently exploited as a colloidal suspension in a flow reactor.[7c] Although the conversions of the heterogeneous system were slightly lower than the homogeneous version, the catalyst had a higher stability. Similarly, Seeberger and Gilmore elegantly expanded on Blechert's work, who initially explored the reactivity of the visible-light semiconductors (C$_3$N$_4$) in a fixed bed photochemical flow reactor, by exploiting this same PC as a moving colloidal catalytic bed in a photochemical flow system.[7d,e]

Recently, our group has exploited the non-covalent immobilization of the cationic PC, bipyridine ruthenium(II) [Ru(bpy)$_3$Cl$_2$], on negatively charged silica (SiO$_2$) particles in order to develop a simple and cost competitive recycling strategy.[6a] This approach was successfully applied to the intensification of the photochemical oxidation of terpenes with singlet oxygen ($^1O_2$) as it enabled an up to ten-fold increase in reaction rate as well as a four-fold improvement in catalyst stability. Given the success of this approach, we were interested in investigating its performance in a continuous flow process where the catalyst is contained in a fixed bed reactor. In order to evaluate how this strategy compares with the batch process, we investigated the photo-oxidation of 1,5-dihydroxynaphtalene (**1,5-DHN**) to produce juglone, which represents a key building block in the synthesis of commercially important anthraquinones.[9] This reaction is highly selective under neutral pH conditions since juglone is obtained as the sole product. Despite the high selectivity of this reaction, juglone remains relatively expensive and difficult to source on large scale. The photo-oxidation of naphtols with photochemically generated $^1O_2$ has been well reported, including using heterogeneous photocatalysis[9d-fe] and once in a continuous flow falling film system.[9g] However, the combination of both has not been reported.

a) Immobilization of photocatalysts (PC) on silica

Cationic PC + SiO₂ → Supported PC (PC@SiO₂)

- Simple operation: mix & filtrate
- Aqueous solvents

b) Application to the photo-oxidation of 1,5-DHN

1,5-dihydroxynaphtalene (**1,5-DHN**) → Juglone

- Supported PC
- Batch vs Flow process
- Light, O₂

Scheme 1. Scope of the study: (a) immobilization of off-the-bench PCs on commercial silica; (b) application to the batch or continuous flow production of juglone.

RESULTS AND DISCUSSION:

Poly-cationic dyes can efficiently interact with negatively charged SiO_2 and this interaction is sufficiently stable to drive adsorption in aqueous mixtures without leaching even after multiple washings.[6a] With this observation in mind, we prepared two classes of PC@SiO₂ by mixing either [Ru(bpy)₃Cl₂] or the sulfonate salt of tetramethylpyridinium porphyrin (TMPyP) in water with commercial SiO_2 (Figure 1).[10] The corresponding adsorbate/adsorbent mixtures were recovered by filtration and the colored powders were used after drying in the photocatalytic reaction without further treatment.

Ru(bpy)₃²⁺   TMPyP⁴⁺
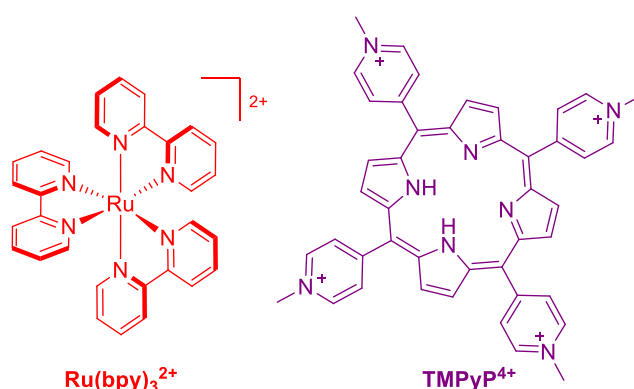
Figure 1. Structures of the two PCs (also named "dyes" or "photosensitizers")[3] used in this study.

We first performed preliminary studies in batch in order to compare the activity of the PCs when used either in solution or supported on SiO_2. Our investigations were carried out using CH_3CN as a solvent as it was found to combine high **1,5-DHN** and oxygen solubility as well as

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a long $^1O_2$ lifetime (81 µs).[11] These series of experiments clearly showed an improved efficiency of the porphyrin dye compared to the organometallic one (Figure 2). These results can be explained by the difference in $^1O_2$ quantum yields between the two sensitizers.[12] Juglone also absorbs visible light (λ_{ab}^{max}= 420 nm) and could therefore compete with the sensitizers absorptions. As porphyrins can be excited at lower energy wavelengths (Q-bands), which are not absorbed by juglone, we speculate that this can also contribute to the higher conversions provided by TMPyP compared to Ru(bpy)$_3$. In the case of TMPyP we were able to measure a maximum Space Time Yield (STY) of 0.22 g.L^{-1}.h^{-1} (conversion of 76% at 0.01 M, 20 °C, 6 h, using TMPyP@SiO$_2$ 4.5 mg/g, 0.16 mol%). Notably, we found that for both PCs, the soluble systems displayed better performances compared to the heterogeneous ones. This difference could be attributed to the fact that the reaction is carried out in a polar solvent which could disfavor the previously reported surface effects.[6a] Indeed, when we performed the same transformation in a mixture of CH$_3$CN/CH$_2$Cl$_2$ (1/1 ratio), the heterogeneous system gave faster conversion to juglone compared to the homogeneous ones, although with lower productivity compared to CH$_3$CN (see ESI, part 9a). Remarkably, in the two heterogeneous systems, no leaching of PC was observed (see ESI, part 9b).
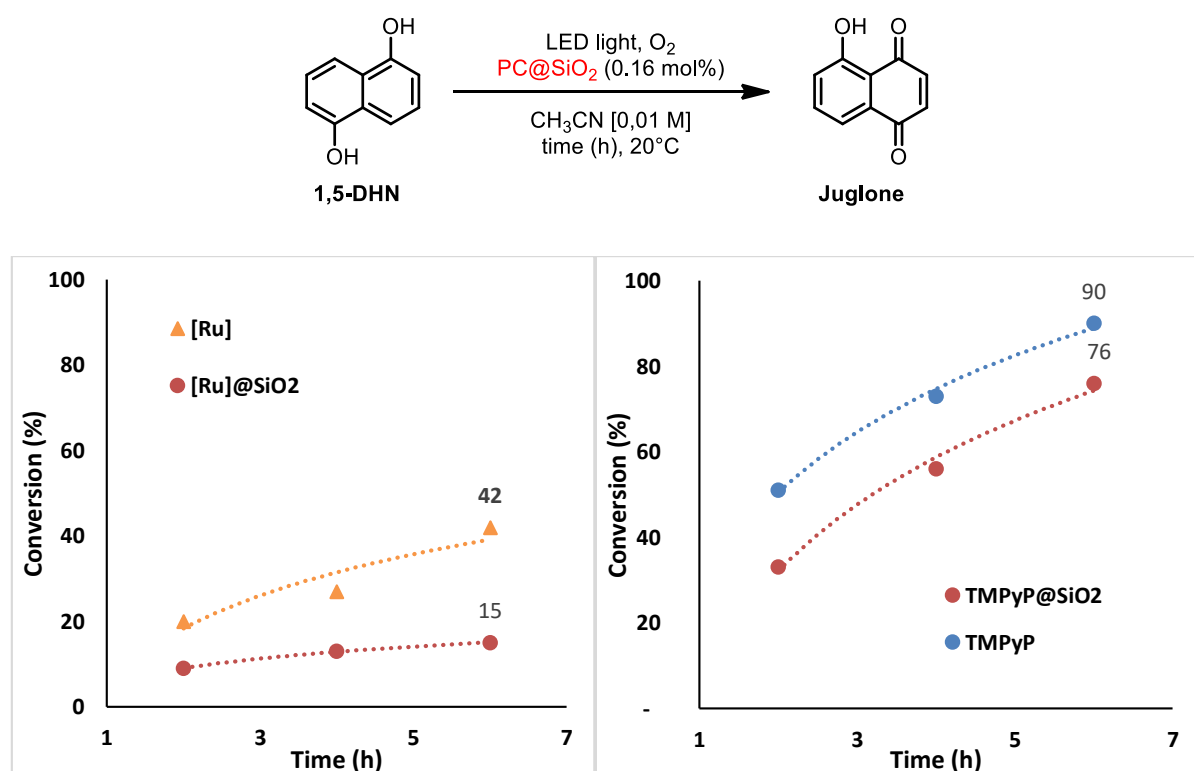

Figure 2. Batch conversions of 1,5-DHN to juglone measured by GC-MS vs time. The reactions were carried out at 20°C in thermo-regulated double jacketed photo-reactors irradiated with white LEDs and continuously oxygenated with air balloons. Experiments were carried out using 100 mL of acetonitrile,

[1,5-DHN] = 0.01 M was used for all trials. [Ru(bpy)$_3$]@SiO$_2$ 2.5 mg/g (0.16 mol%) and of [TMPyP]@SiO$_2$ 4.5 mg/g (0.16 mol%) were used.[13]

Given the known advantages of flow over batch chemistry, such as mixing, heat and mass transfers, and control of residence time, the synthesis of juglone was investigated using a home-made flow photo-reactor (Figure 3).[14] Briefly, the reactor consists of a transparent tube containing the PC@SiO$_2$ catalyst (1.3 g per cartridge, 1/4'' PTFE tubing, vol = 1.5 mL) stoppered with cotton wool.[15] Continuous irradiation was carried out with white LED strips surrounding the tube. The substrate was delivered by means of an HPLC pump and oxygen or air was dosed via a high pressure switching valve (Rheodyne) The reactants were mixed via a T-piece prior to entering the reactor. As explained above, the advantage of this design is that the fixed catalytic bed will generate a localized increase in PC concentration. The concentrations of PC are therefore supposed to be significantly higher than in the corresponding batch process. The heat generated by the LEDs was expelled by a fan localized under the reactor. This allowed to maintain an average temperature of 24°C throughout the entire operation.
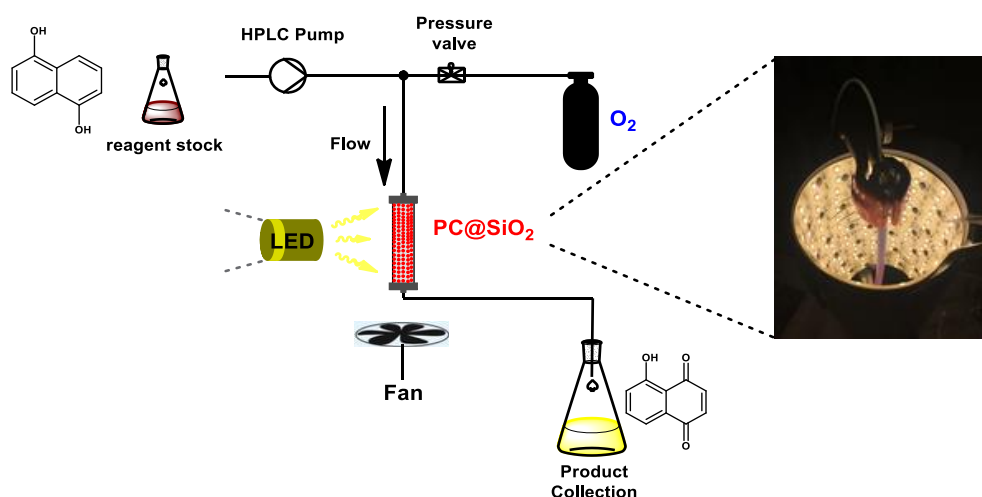

Figure 3. Representation of the home-made flow photo-reactor (1/4'' PTFE tube, vol = 1.5 mL), fitted with 1/16'' pipes connected to the different components using Swagelok fittings. A fan is added at the bottom to remove the heat generated by LEDs.

Our first experiment started with [Ru(bpy)$_3$]@SiO$_2$ 2.5 mg/g, by using a substrate concentration of 0.006 M, air as an oxygen source and a residence time of 15 min (Table 1, entry 1). This gave a stable and clean conversion of 81 % in juglone with no apparent loss of activity during the time of the experiment. By keeping all parameters the same but replacing air with pure oxygen, the conversion increased to 96 % without formation of any side product or degradation

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(entry 2). Increasing the organic flowrate to 1.0 mL·min^{-1} and the oxygen flowrate to 1.0 mL·min^{-1} resulted in a decrease in conversion to 40 % (entry 3). Increasing the concentration to 0.01 M had similar effects, leading to a conversion of 45 % (entry 4). By modifying the catalyst to TMPyP@SiO$_2$ 4.5 mg/g but maintaning all other parameters the same, a promising yield of 77 % was obtained (entry 7). This result is equivalent to a STY of 5.35 g.L^{-1}.h^{-1}. By adding a second cartridge, which is equivalent to a 2-fold increase in residence time (30 min), the conversion reached 78 % and 100 % for Ru(bpy)$_3$ and TMPyP respectively (entries 6 and 8). While increasing the concentration provided lower yields, in all these experiments a steady conversion was maintained for 6 to 8 hours of run showing no catalyst deactivation throughout the entire operation.

Table 1: optimization of the photo-oxidation of 1,5-DHN in a continuous flow fixed bed photoreactor
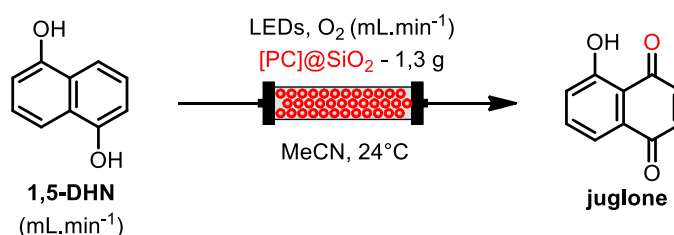
Entry	PS	[1,5-DHN] mol/L	Flow rate (mL·min)	Number of cartridge	O$_2$ source (mL·min)	Yield (% GC-MS)
1	Ru(bpy)$_3$Cl$_2$	0.006	0.1	1	Air (0.2)	81
2	Ru(bpy)$_3$Cl$_2$	0.006	0.1	1	O$_2$ (0.2)	96
3	Ru(bpy)$_3$Cl$_2$	0.006	1.0	1	O$_2$ (1.0)	40
4	Ru(bpy)$_3$Cl$_2$	0.01	0.1	1	O$_2$ (0.2)	45
5	Ru(bpy)$_3$Cl$_2$	0.01	0.1	2	O$_2$ (0.2)	78
6	TMPyP	0.006	0.1	1	O$_2$ (0.2)	100
7	TMPyP	0.01	0.1	1	O$_2$ (0.2)	77
8	TMPyP	0.01	0.1	2	O$_2$ (0.2)	100
9	TMPyP	0.05	0.1	2	O$_2$ (0.2)	40
10	TMPyP	0.1	0.1	2	O$_2$ (0/2)	15

CONCLUSIONS

In conclusion, a simple catalyst immobilization strategy was developed allowing to easily interchange a commercially available photocatalyst or photosensitizer on inexpensive and readily available SiO$_2$ to generate ^{1}O$_2$ and produce the commercially important synthetic intermediate juglone. This proved to be a highly efficient approach for the synthesis of juglone in batch and in flow with STYs of 0.22 g.L^{-1}.h^{-1} and 5.35 g.L^{-1}.h^{-1} respectively when using TMPyP as a sensitizer. In all our experiments, no leaching was observed and the production remained stable throughout the entire time of our experiments (typically 6 to 8 h). In addition, this low pressure flow process can incorporate multiple cartridges in series without increasing

its footprint. Its potential to be easily and safely reproduced in other laboratories should also be underlined as this low pressure reactor does not require specialized engineering and expensive high pressure equipment. This photochemical production approach should therefore find more widespread applications in organic synthesis.

EXPERIMENTAL SECTION

General procedure for batch reactions

Homogeneous conditions

A 100 mL solution of 1,5-DHN (concentration depending of the experiment) was prepared in a given solvent and sonicated for 3 min. Then, 1 mL from a 10 mL solution of photocatalyst (0.16 mol% in relation to 1,5-DHN) in the same solvent was added to the solution of 1,5-DHN. The solution was then transferred in the thermo-regulated batch reactor. An oxygen balloon with a needle bubbling in the liquid was used to continuously oxygenate the solution throughout the entire experiment with slow magnetic stirring. The reactor was irradiated by LEDs and the temperature was maintained at 20 °C.

Heterogeneous conditions

A 100 mL solution of 1,5-DHN (concentration depending of the experiment) in a given solvent was prepared to which supported photosensitizer (*quantum satis* 0.16 mol% equivalent of TMPyP) on silica was added. The slurry was then transferred in the thermo-regulated batch reactor. An oxygen balloon with a needle bubbling in the liquid was used to continuously oxygenate the solution throughout the entire experiment with slow magnetic stirring. The reactor was irradiated by LEDs and the temperature was maintained at 20 °C.

General procedure for continuous flow reactions

A solution of 1,5-DHN (concentration depending of the experiment) was prepared in 100 mL of acetonitrile, sonicated for 3 min and protected from light with an aluminum foil. After this the cartridge was filled with 1.3 g of supported PS and placed at the center of a tube where LED strips are attached. The 1,5-DHN solution was pumped in the system at a constant flow rate throughout the entire experiment.

ASSOCIATED CONTENT

Supporting information

The supporting information is available free of charge on the ACS Publications website at DOI:

General procedures, reaction analysis and spectroscopic characterizations of photocatalysts and product.

AUTHOR INFORMATION

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Notes
The authors declare no competing financial interest.

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