Robust Organic Photosensitizers Immobilized on a Vinylimidazolium Functionalized Support for Singlet Oxygen Generation under Continuous-Flow Conditions

Koichiro Masuda, a Yao Wang, a,b Shun-ya Onozawa, a,b Shigeru Shimada, b Nagatoshi Koumura, b Kazuhiko Sato b and Shū Kobayashi a,b

a Department of Chemistry, School of Science, The University of Tokyo. 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033 Japan
b Interdisciplinary Research Center for Catalytic Chemistry, National Institute of Advanced Industrial Science and Technology (AIST). Central 5, 1-1-1 Higashi, Tsukuba, Ibaraki, 305-8565 Japan
* shu_kobayashi@chem.s.u-tokyo.ac.jp; s-onozawa@aist.go.jp

Supporting Information

<General>

1H and 13C NMR spectra were recorded on JEOL ECX400 spectrometer in CDCl3 unless otherwise noted. Tetramethylsilane (TMS) served as internal standard (δ = 0) for 1H NMR, and CDCl3 served as internal standard (δ = 77.16) for 13C NMR. Gas chromatography was measured on a SHIMADZU GC-2014 spectrometer with N2 gas as a career, using Agilent DB-1 column (Length: 30 m, I.D.: 0.250 mm, Film: 0.25 µm). Energy dispersive X-ray spectroscopy was measured on a SHIMADZU EDX-800HS spectrometer. Elemental analysis was measured on a PerkinElmer 2400II analyzer. UV-vis spectroscopy was measured on JASCO V-550 spectrometer. The reaction was carried out using appropriate length of white 5050 3 chip tape LED (provided from LED PARADISE: LE-5060H252W-3 InGaN dice with yellow diffused lens, 240 mW per bulb) as the light source. Mass flow controller (MFC, SEC-E40) was purchased form HOLIBA, Ltd. Pump (UI-22) and PTFE tube were purchased from FLOM, Inc. Merrifield resin (chloride content: 1.9 mmol/g), Rose Bengal, 1-vinylimidazole, 1-allylimidazole, 1-butylimidazole, t-butyl imidazole, 2-ethylthio-ethanol, α-terpinene, 1,3,5-trimethoxybenzene and pentadecane were purchased from Tokyo Chemical Industry Co., Ltd. 1-methylimidazole, 1-ethylimidazole and triphenylphosphine were purchased from FUJIFILM Wako Pure Chemical Corporation. Triethylamine was purchased from Kanto Chemical Co., Inc. and 1,2-dichloroethane was
purchased from Kishida Chemical Co., Ltd. Ion exchange resins were purchased from ORGANO and Sigma-Aldrich.

<Catalyst preparations and evaluations>

A: catalysts using commercially available supports

All catalysts using commercially available supports were prepared as follows. Rose Bengal (0.5 g) was dissolved in 150 mL pure water, Amberlyst A26 (OH) (5.0 g) was added to the resulting solution. This mixture was stirred at room temperature for 2 h. After filtration, the residue was washed with water, methanol, dichloromethane and finally washed with dichloromethane in the Soxhlet extractor under reflux conditions until the solvent in the extractor became colorless. Filtration and desiccation afforded the catalyst (2.1720 g).

B: PS-imidazolium supports & PS-triethylammounium support

All catalysts using imidazolium supports and ammonium support were prepared as follows. To a solution of 1-vinylimidazole (0.48 ml, 5.25 mmol, 1.05 equiv) and mesitylene (approx. 0.5 ml, internal standard) in acetonitrile (50 ml), Merrifield resin (1.9 mmol/g - Cl, 2.6316 g, 5 mmol, 1.0 equiv) and NaI (37.5 mg, 0.25 mmol, 0.05 equiv) were added at room temperature. The reaction mixture was stirred (overhead stirring) under reflux condition until the consumption of the imidazole became constant (monitored by GC). After filtration, the residue was washed with acetonitrile, ethyl acetate, acetone, water, acetone, ethyl acetate and dichloromethane. Drying at 40 °C in the vacuum oven afforded the PS-vinylimidazolium support (3.0359 g, loading of imidazole: 0.674 mmol/g, determined by the consumption of imidazole).

Rose Bengal (3.1246 g, 3.07 mmol, 1.5 equiv) was dissolved in 250 mL pure water, PS-vinylimidazolium support (3.0359 g, 2.05 mmol imidazolium group, 1.0 equiv) was added to the resulting solution. This mixture was stirred at room temperature for 2 h. After filtration, the residue was washed with water, methanol, dichloromethane and finally washed with dichloromethane in the Soxhlet extractor under reflux conditions until the solvent in the extractor became colorless. Filtration and desiccation afforded the RB@PS-vinylimidazolium catalyst (3.9775 g, loading of RB: 0.12 mmol/g (determined by EDX analysis)).
**<Batch reactions>**

All the batch reactions were performed as follows. To a Schlenk tube containing supported Rose Bengal catalyst on IRA900 (30 mg), α-terpinene (48.5 μL, 0.3 mmol) and 3 ml 1,2-dichloroethane, a balloon filled with air was attached. The mixture was stirred at room temperature under the irradiation of 3 white LED bulbs for 3 hours. Filtration and evaporation of the solvents afforded the crude product containing ascaridole (82%, determined by NMR using 1,3,5-trimethoxybenzene as an internal standard).

**Ascaridole<sup>[1]</sup> (1)**

$^1$H NMR (CDCl<sub>3</sub>) δ = 6.50-6.40 (dd, 2H, J = 8.6 Hz; J = 33.5 Hz, -CH=CH-), 2.04-2.00 (m, 2H, -CH<sub>2</sub>- near -iPr), 1.96-1.89 (m, 1H, -CH(CH<sub>3</sub>)<sub>2</sub>), 1.53-1.51 (d, 2H, J = 10.0 Hz, -CH<sub>2</sub>- near -Me), 1.38 (s, 3H, -CH<sub>3</sub>), 1.01-0.99 (d, 6H, J = 7.0 Hz, -CH(CH<sub>3</sub>)<sub>2</sub>). GC: r.t. = 38.5 min (50 °C: 30 min; rate: 10°C/min; 250 °C: 10 min)

**<Flow reactions>**

All the flow reactions were performed as follows. 220 mg RB@PS-vinylimidazolium catalyst were packed into a PTFE tube (ID: 2 mm; OD: 3 mm; L: 10 cm), with in-line filter devices for both ends (Figure S1). This tube was used as the column for the flow reaction (Figure S2). 0.1 mol/L α-terpinene in 1,2-dichloroethane was prepared as the reaction solution (kept at 0 °C), using 0.018 mol/L pentadecane as the internal standard (to determine the yield). This mixture (flow rate: 0.02 ml/min) was combined with air (0.5 ml/min, MFC: 100 SCCM) and introduced to the column. 3 white bulbs were used as the light source (Figure S3). The reaction mixture was collected for 1 h and analyzed by GC to determine the yield.

![Figure S1. Schematic image of the tube-column filled with catalyst](image-url)
Figure S2. Whole structure of our hand-made flow system. A Cooling bath for the reactor was removed for clarity.

Figure S3. Tape LED attached in a beaker (left) and the system under operation (right)
**p-Cymene (2)**

GC: r.t. = 24.9 min (50 °C: 30 min; rate: 10 °C/min; 250 °C: 10 min) (no isolation, compared with the commercially available reagent)

**Triphenylphosphine oxide**

1H NMR (CDCl₃) δ = 7.70-7.65 (m, 6H), 7.56-7.52 (m, 3H), 7.48-7.44 (m, 6H); 13C NMR (CDCl₃) δ = 132.3, 132.2, 132.0, 128.7, 128.6; 3¹P NMR (161.8 MHz, CDCl₃) δ = 29.5. GC: r.t. = 17.4 min (50 °C: 2 min; rate: 20°C/min; 250 °C: 10 min)

**2-(ethylsulfinyl)ethan-1-ol**

1H NMR (CDCl₃) δ = 4.20-4.13 (m, 2H, -CH₂OH), 3.43-3.40 (t, 1H, J = 5.5 Hz, -OH), 2.96-2.78 (m, 4H, -CH₂SO-CH₂-), 1.38-1.34 (t, 3H, J = 7.5 Hz, -CH₃); 13C NMR(CDCl₃) δ = 55.7, 53.6, 45.9, 6.8. GC: r.t. = 7.6 min (50 °C: 2 min; rate: 20°C/min; 250 °C: 10 min)

**2-(ethylsulfonyl)ethan-1-ol**

1H NMR (CDCl₃) δ = 4.15-4.11 (dd, 2H, -CH₂OH), 3.21-3.18 (t, 2H, -CH₂CH₂OH), 3.14-3.09 (q, 2H, -CH₂CH₃), 2.54-2.51 (t, 1H, -OH), 1.44-1.40 (t, 3H, -CH₃); 13C NMR(CDCl₃) δ = 56.1, 54.1, 48.9, 6.3. GC: r.t. = 8.2 min (50 °C: 2 min; rate: 20°C/min; 250 °C: 10 min)
<Miscellaneous>

Figure S4 Merrifield-vinylimidazolium catalyst after 11 days continuous flow operation.

Figure S5 Merrifield-allylimidazolium catalyst after 3 h batch reactions. Obvious bleaching of Rose Bengal was observed.

Figure S6. UV-Vis analysis of reaction mixture. Reaction mixture was collected before LED was turned on (Control) and after operation started (3 – 5 h, 6.5 – 8.5 h and 9.5 – 11.5 h), and were analyzed directly with 1.0 cm quartz cuvette. Control experiment exhibits obvious absorption spectra of starting material, and absorption spectrum of product 1 and 2 are clearly shown in the other samples. There are no obvious absorptions in any sample at around 560 or 510 nm, indicating no RB molecule or its decomposed product are leaching into reaction mixture during flow reactions.
Figure S7 Solid-state $^{13}$C NMR spectra of Merrifield-vinylimidazolium catalysts. A signal of terminal carbon of vinyl group (110–115 ppm) obviously decreased after a continuous flow operation.

<References>


Figure S8. $^1$H NMR spectra of ascaridole (1) with trimethoxybenzene (This compound was not stable and was not isolated with other impurities)

Figure S9. $^1$H NMR spectra of triphenylphosphine oxide
Figure S10. $^{13}$C NMR spectra of triphenylphosphine oxide

Figure 11. $^{31}$P NMR spectra of triphenylphosphine oxide
Figure S12. $^1$H NMR spectra of 2-(ethylsulfinyl)ethan-1-ol

Figure S13. $^{13}$C NMR spectra of 2-(ethylsulfinyl)ethan-1-ol
Figure S14. $^1$H NMR spectra of 2-(ethylsulfonyl)ethan-1-ol

Figure S15. $^{13}$C NMR spectra of 2-(ethylsulfonyl)ethan-1-ol