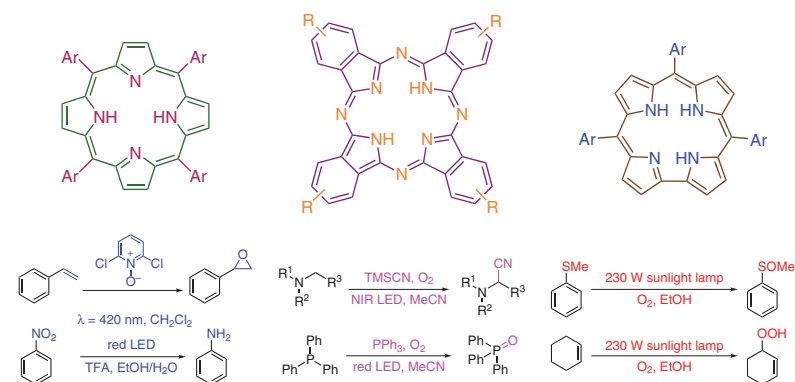


Exploring Porphyrins, Phthalocyanines and Corroles as Photocatalysts for Organic Transformations

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Abstract In recent years, macrocycles have emerged as efficient and sustainable photosensitizers for the catalysis of organic transformations. This graphical review provides a concise overview of photocatalysis and photoredox catalysis utilizing three common macrocycles: porphyrins, phthalocyanines and corroles. They exhibit strong absorption in the visible region and can be easily oxidized or reduced, making them good candidates for photocatalysis.

Key words photocatalysis, photoredox catalysis, porphyrins, phthalocyanines, corroles

Photocatalysis offers the advantage of using light as an affordable, sustainable and green source of energy to carry out endergonic reactions.¹ It offers the advantage of milder conditions over those of thermal reactions.² As visible light is absorbed by sensitizers but not by most organic compounds, it offers an efficient approach to prevent product degradation and side reactions.³ In photoredox catalysis, the photocatalyst in its excited state differs from that of the ground state by providing a higher electron affinity and a lower ionization potential, thereby making it a better electron donor as well as an acceptor. Versatile applications of photocatalysts are found in CO₂ reduction, H₂O splitting, proton-coupled electron transfer, photovoltaics and in the development of photo-electrochemical solar cells.⁴

The formation of carbon–carbon and carbon–heteroatom bonds has been a challenge in organic chemistry, which has been efficiently tackled by photocatalysis.⁵ Traditionally, metal complexes (such as Ru and Ir polypyridyl complexes) and organic dyes (such as eosin Y) have been employed extensively as photocatalysts.⁶ However, the high cost and toxic nature of metal complexes, as well as the pH-sensitive nature of organic dyes have prompted researchers to explore macrocycles such as porphyrins, phthalocyanines and corroles for photocatalysis.⁷ These macrocycles have been examined for the catalysis of cyclopropanations, hydroxylations, aziridinations, epoxidations, sulfoxidations, etc.^{8–10} Typically in photoredox catalysis, under light irradiation, these photocatalysts may undergo oxidation or reduction at different potentials and participate in SET (single-electron transfer) with the substrates. In photooxidation reactions, upon photoexcitation, such catalysts can switch from singlet to triplet excited states via ISC (intersystem crossing), and during this process, they can generate singlet oxygen via the type II pathway. Their ability to participate in SET depends on the reaction conditions, the nature of the substrate and also on the types of meso-substituents (electron-donating or electron-withdrawing) present on the catalyst, which in turn will govern their efficiency. This graphical review provides an overview of organic transformations photocatalyzed by porphyrins, phthalocyanines and corroles, along with selected substrate scopes, that have been reported over the last five years (2019 to 2023). As photocatalysis by corroles is relatively less explored, all the examples described since 2005 are included. This graphical review describes photooxidations, epoxidations, sulfoxidations, aziridinations and cyanations of aliphatic and/or aromatic compounds by employing these macrocycles. In addition, C–H arylations of heteroarenes and thiocyanations utilizing porphyrins are discussed. Researchers have also explored hydroxylations, cycloadditions, perfluoroalkylations and phosphonylations by employing phthalocyanines as photocatalysts. Examples of brominations mediated by corroles are also provided. However, reactions involving inorganic transformations, polymerization, photodegradation and heterogenous catalysis are excluded.

Biographical Sketches



Ashmita Jain received her M.Sc. in chemistry from Jamia Millia Islamia, India. In 2021, she began her Ph.D. research

at the Indian Institute of Technology Gandhinagar, India with Dr. Iti Gupta. Her research is focused on photocatalyt-

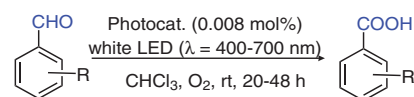
ic transformations of organic compounds utilizing macrocycles such as corroles and their metal complexes.



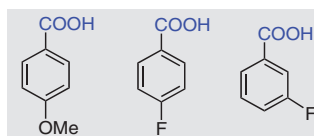
Iti Gupta obtained her Ph.D. in chemistry from the Indian Institute of Technology Bombay, India. She received a JSPS Fellowship from Japan and undertook postdoctoral research at Kyushu University, where she worked on expanded porphyrins. Subsequently, she joined the Chemistry

Faculty at BITS Pilani, K K Birla Goa Campus (2007–2009), before moving to the Indian Institute of Technology Gandhinagar in July 2009, where she is currently an associate professor. She is a member of the Society of Porphyrins & Phthalocyanines, and is also a life-member of the Chemical

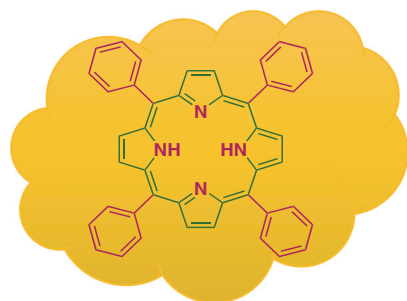
Research Society of India. Her current research interests are focused on the applications of porphyrins, corroles and metal dipyrinato complexes in photocatalysis and the photodynamic therapy of cancer.

Oxidation of aldehydes to carboxylic acids by photosensitizers¹¹


Selected substrate scope

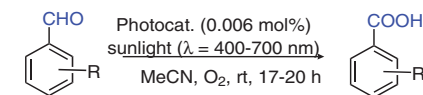


Yield by P2: 60% (4-methoxy), 87% (4-fluoro), 97% (2-fluoro)

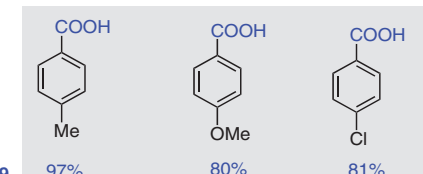

Photophysical properties of porphyrin^{12,13}

5,10,15,20-tetraphenylporphyrin in DCM

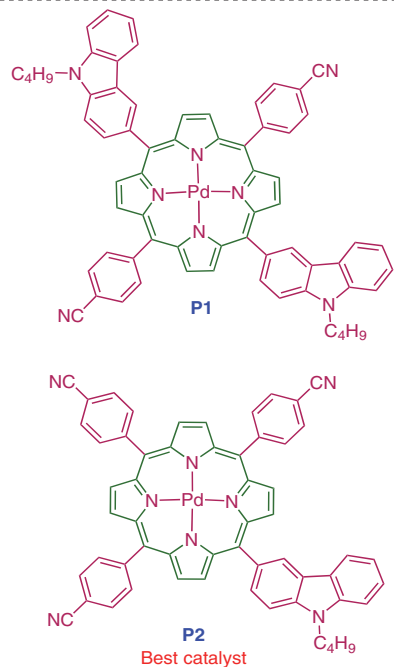
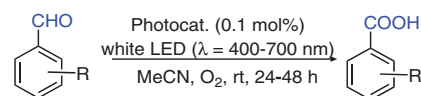
- one Soret and four Q bands in UV-vis spectra
Soret band- 417 nm
Q-bands- 514 nm, 549 nm, 592 nm, 647 nm
- Fluorescence quantum yield (ϕ_f) = 0.11
- Fluorescence lifetime (τ_f) = 9.62 ns

(12) Owens, *Inorganica Chim. Acta.* **1998**, 279, 226-231.(13) Ghosh, *J. Phys. Chem. B.* **2003**, 107, 3613-3623.
Oxidation of aldehydes to carboxylic acids under sunlight by photosensitizers¹⁵


Selected substrate scope

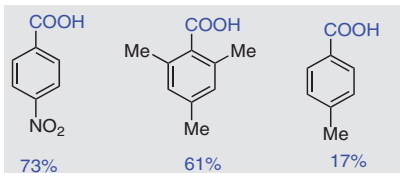


Yield by P9: 97% (4-methyl), 80% (4-methoxy), 81% (4-chloro)

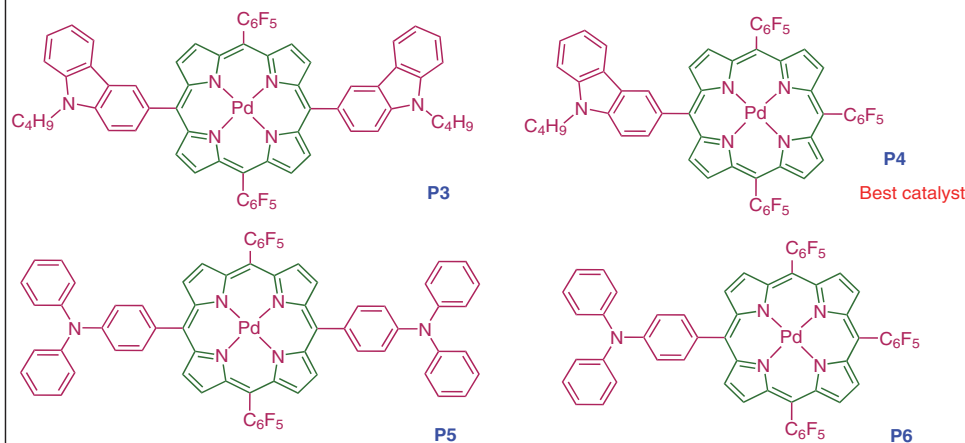
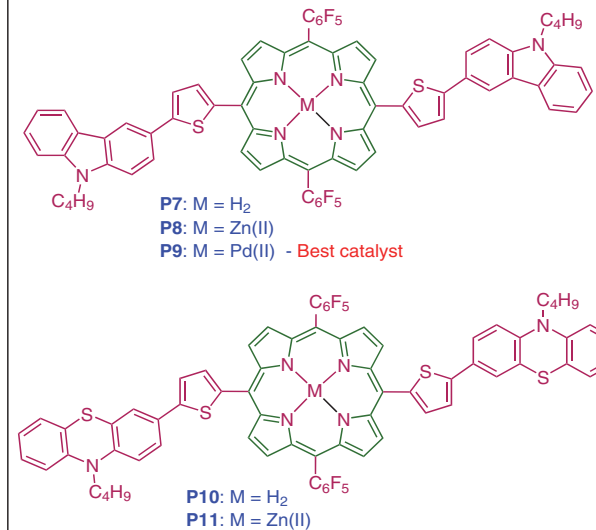
(11) Gupta, *J. Porphyrins Phthalocyanines* **2021**, 25, 571-581.
White LED induced oxidation of aldehydes by photosensitizers¹⁴


Yield by P4

Selected substrate scope

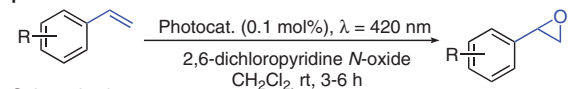


73% (4-nitro), 61% (2,4-dimethyl), 17% (4-methyl)

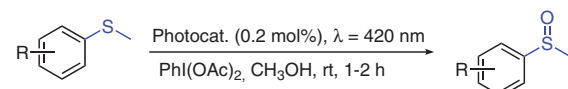
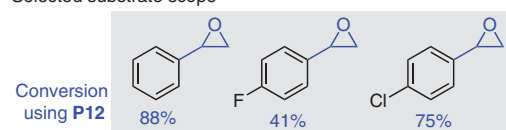
(14) Gupta, *Inorganica Chim. Acta.* **2020**, 502, 119339-119348.(15) Gupta, *Dyes Pigm.* **2023**, 209, 110861-110872

- On comparing the yield for oxidation of aldehyde to carboxylic acid, P9 shows best catalytic activity among P1-P11.

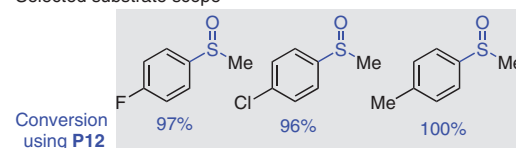
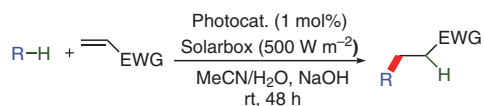
Further Reading
(16) Shaabani, *Tetrahedron Lett.* **2010**, 51, 4061-4065.(17) Manesh, *J. Porphyrins Phthalocyanines* **2012**, 16, 93-100.
Figure 1 Photocatalytic oxidation of aldehydes by porphyrins¹¹⁻¹⁷

Photocatalytic epoxidation of styrenes and sulfoxidation of thioanisoles by photosensitizers¹⁸


Selected substrate scope

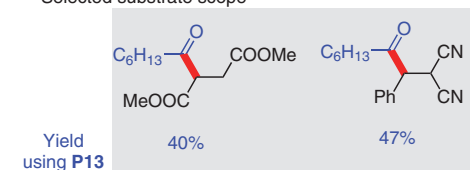
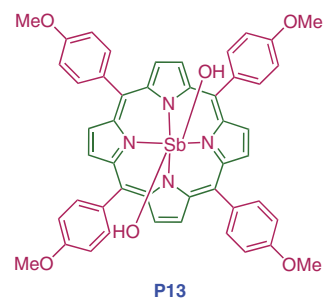
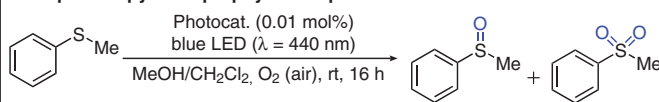


Selected substrate scope

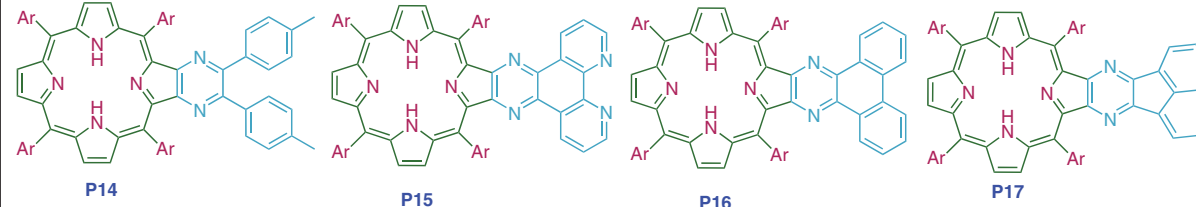
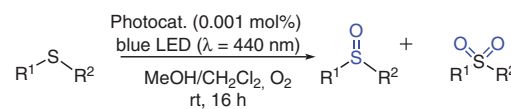
(18) Zhang, *New J. Chem.* **2021**, 45, 4977.
Antimony porphyrin as a photoredox catalyst for C–H to C–C bond conversion¹⁹


EWG: Electron-Withdrawing Group

Selected substrate scope

(19) Ravelli, *ACS Catal.* **2020**, 10, 9057.
 π -Expanded porazinoporphyryns as photosensitizers for sulfoxidation²⁰


	Conversion	Selectivity Sulfoxide	Sulfone
P14	89%	98%	2%
P15	100%	99%	1%
P16	100%	99%	1%
P17	100%	99%	1%

(20) Tsvadze, *Dyes Pigm.* **2023**, 210, 110935.
Diaryl porazinoporphyryns as photosensitizers for sulfoxidation²¹


Selected substrate scope

	Conversion using P19	Selectivity Sulfoxide	Sulfone
Phenyl	100%	98%	2%
Allyl	100%	100%	0%

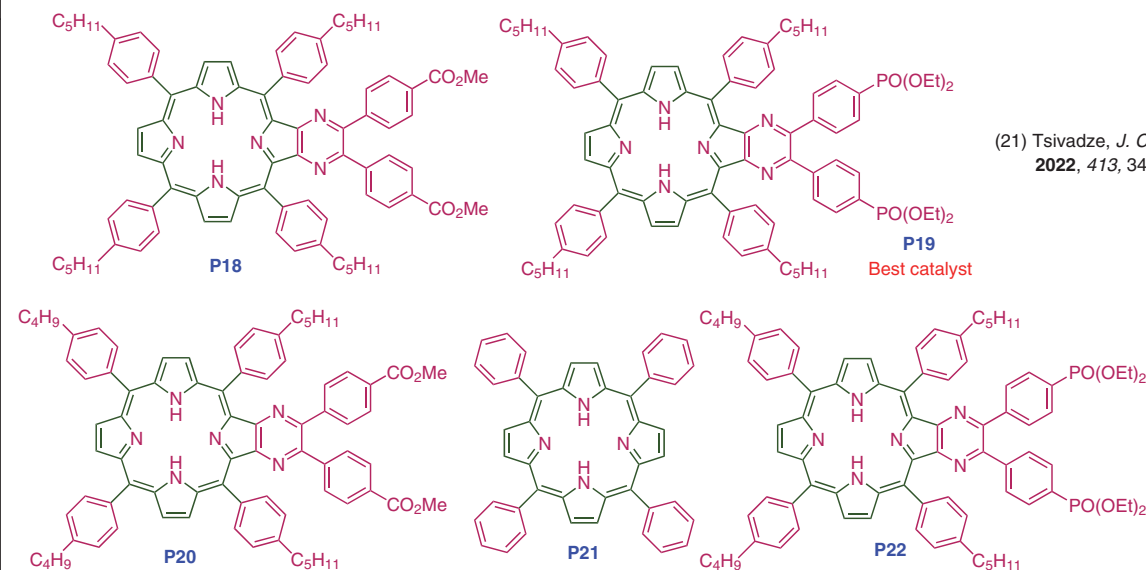
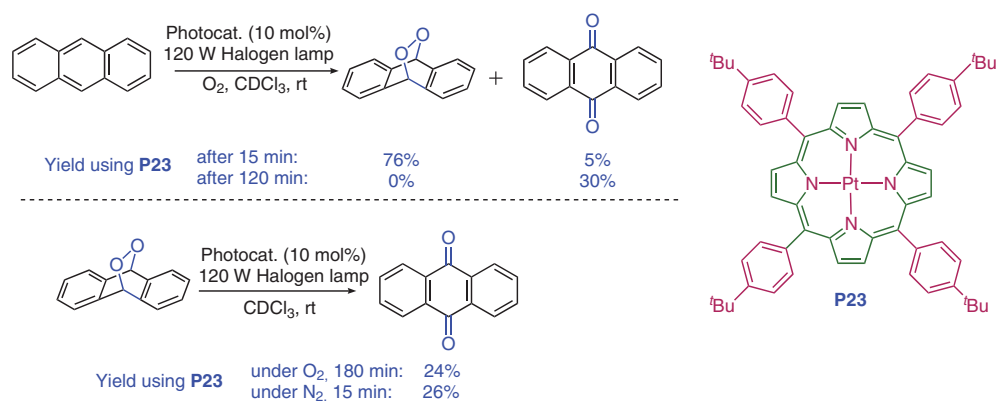
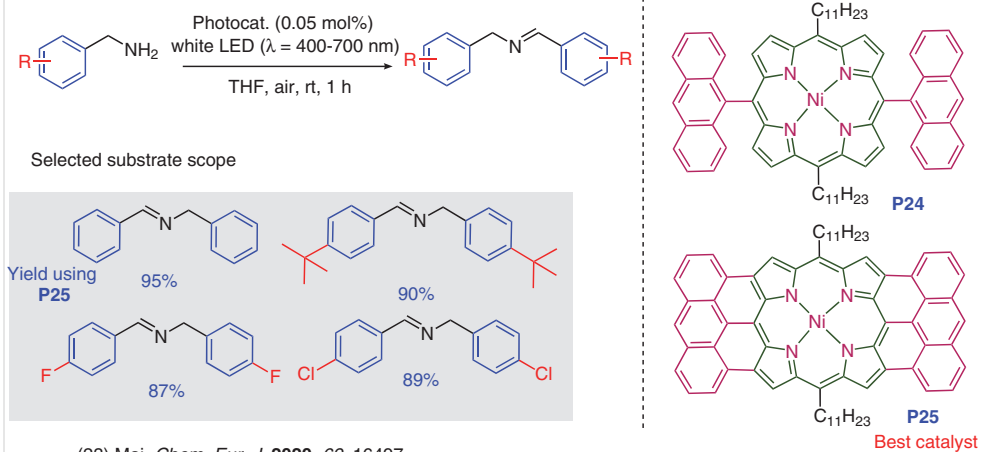
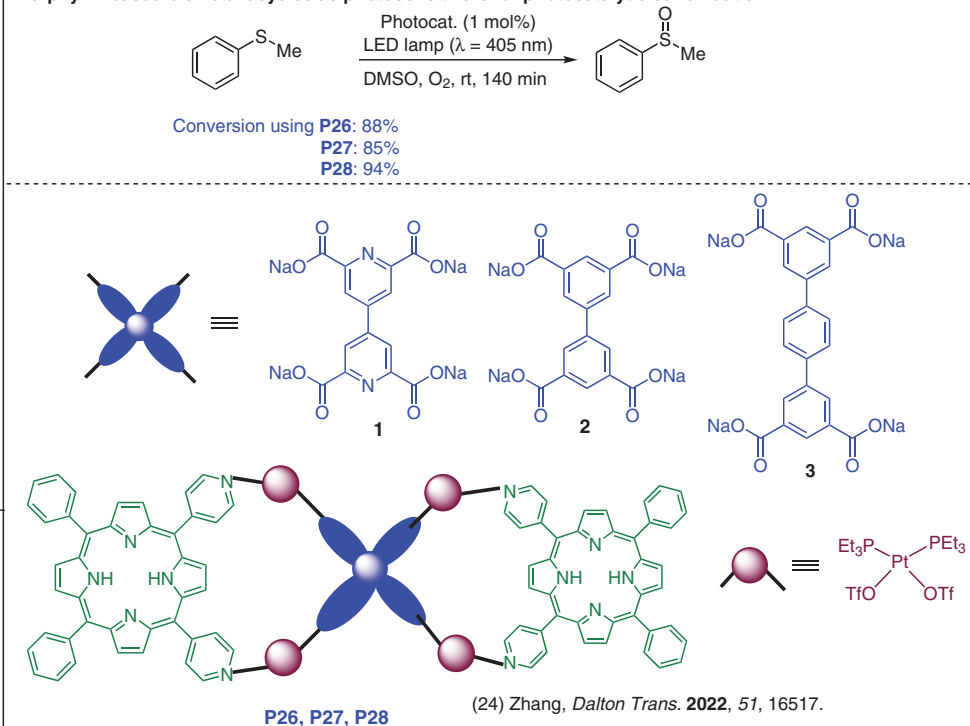
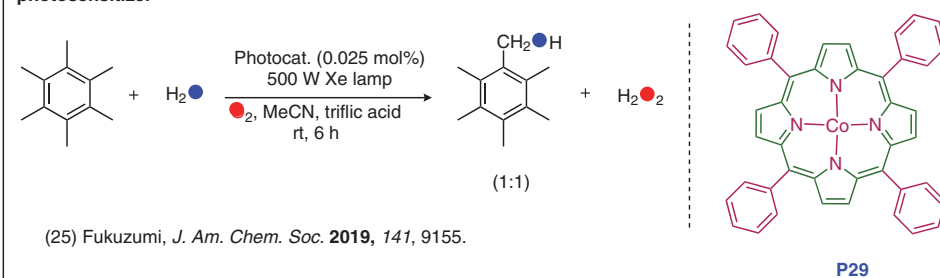
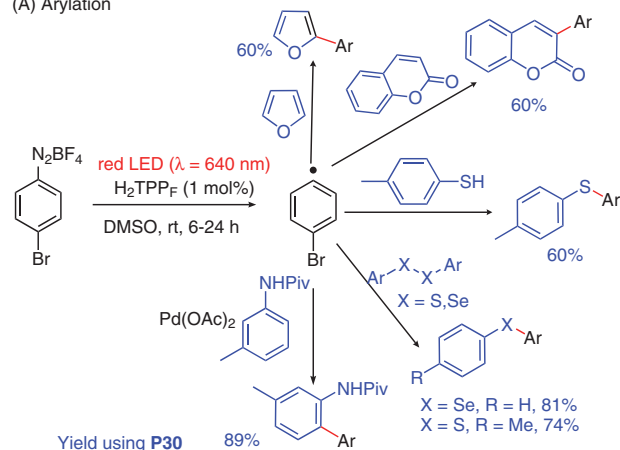
(21) Tsvadze, *J. Catal.* **2022**, 413, 342.
Figure 2 Photocatalytic epoxidation of styrenes, sulfoxidation of thioanisoles and C–H activation of alkenes by porphyrins^{18–21}

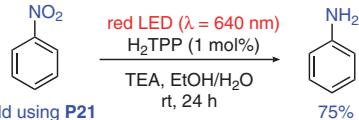
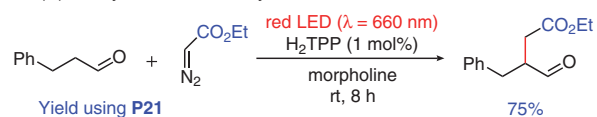
Photo-oxidation of anthracene using porphyrins as photosensitizers²²
(22) Sugiura, *Tetrahedron Lett.* **2019**, *60*, 151081.
Bis-anthracene-fused porphyrins as photoredox catalysts for oxidative coupling of benzylamines²³
(23) Mai, *Chem. Eur. J.* **2020**, *69*, 16497.
Porphyrin-based bimetallics as photosensitizers for photocatalytic sulfoxidation²⁴

Photocatalytic oxygenation of hexamethylbenzene using water as an oxygen source and O₂ as an oxidant with a photosensitizer²⁵

Figure 3 Photocatalytic oxidation of anthracene, benzyl amine coupling, sulfoxidation of thioanisole and oxygenation of hexamethylbenzene by porphyrins^{22–25}

Red-light-induced photoredox catalysis²⁶

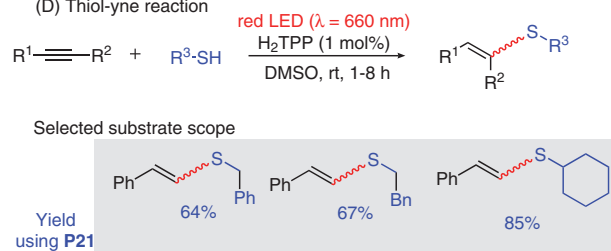
(A) Arylation



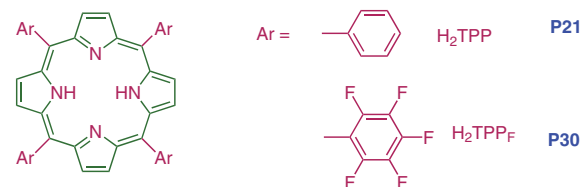
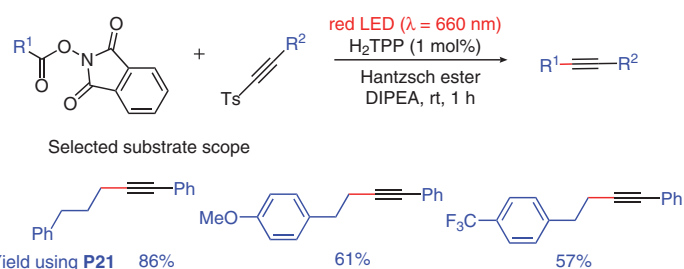
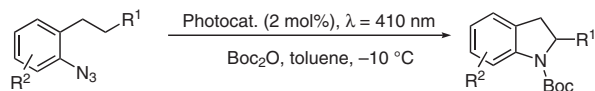
(B) Reduction of nitrobenzenes

(C) α -Alkylation of an aldehyde

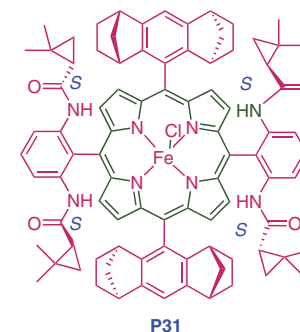
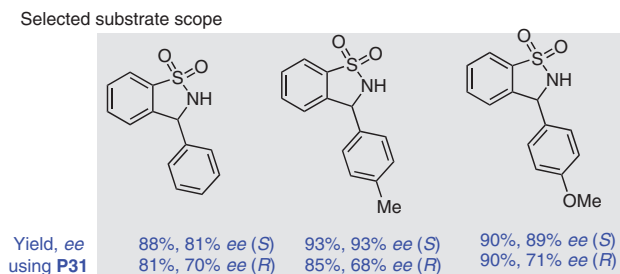
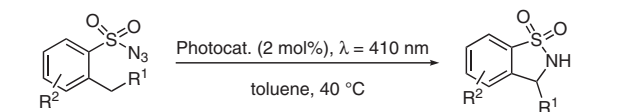
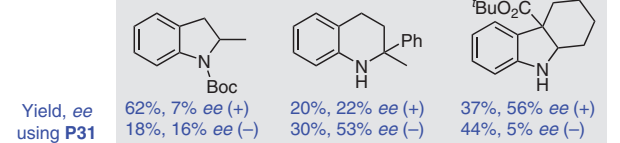
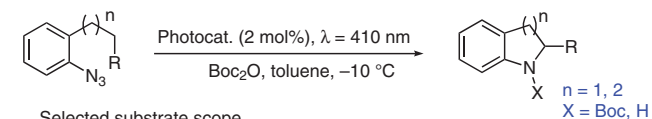
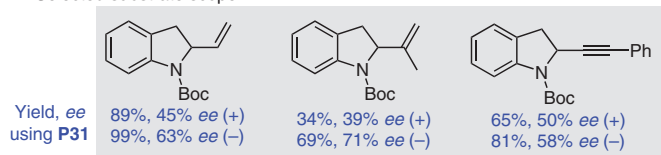
(D) Thiol-yne reaction

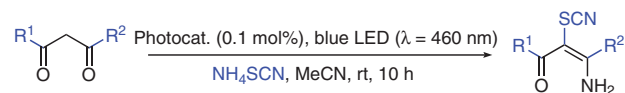


(E) Decarboxylative alkylation

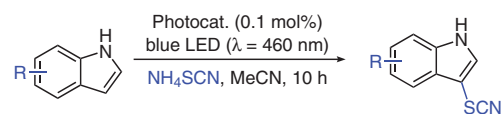
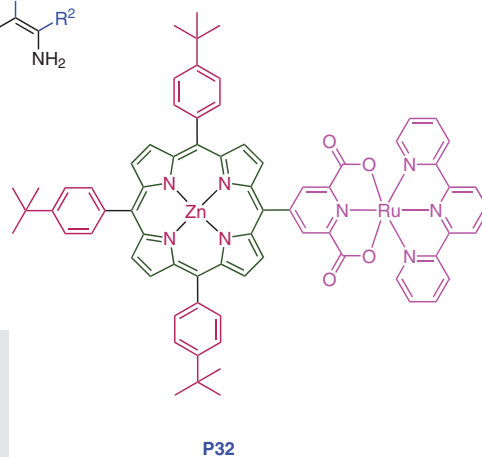
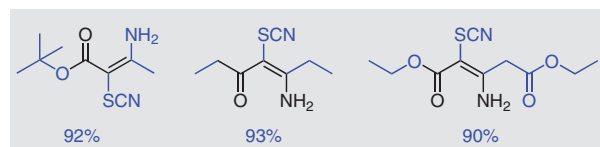
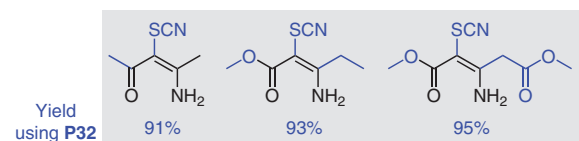
(26) Gryko, *ACS Org. Inorg. Au* 2022, 2, 422.Enantioselective C–H bond amination by a chiral iron porphyrin as the photosensitizer²⁷

Selected substrate scope

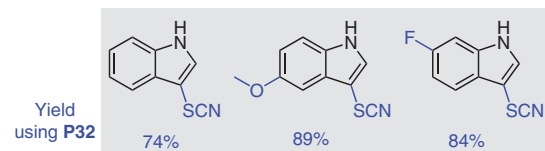
(27) Che, *Angew. Chem. Int. Ed.* 2023, 62, e202303981.Figure 4 Photoredox catalysis and C–H bond amination by porphyrins^{26,27}

Photocatalytic thiocyanation using a ruthenium-porphyrin complex as a photosensitizer²⁸


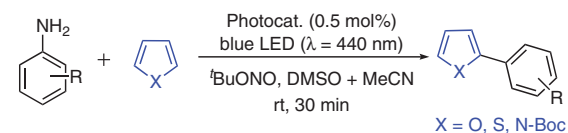
Selected substrate scope



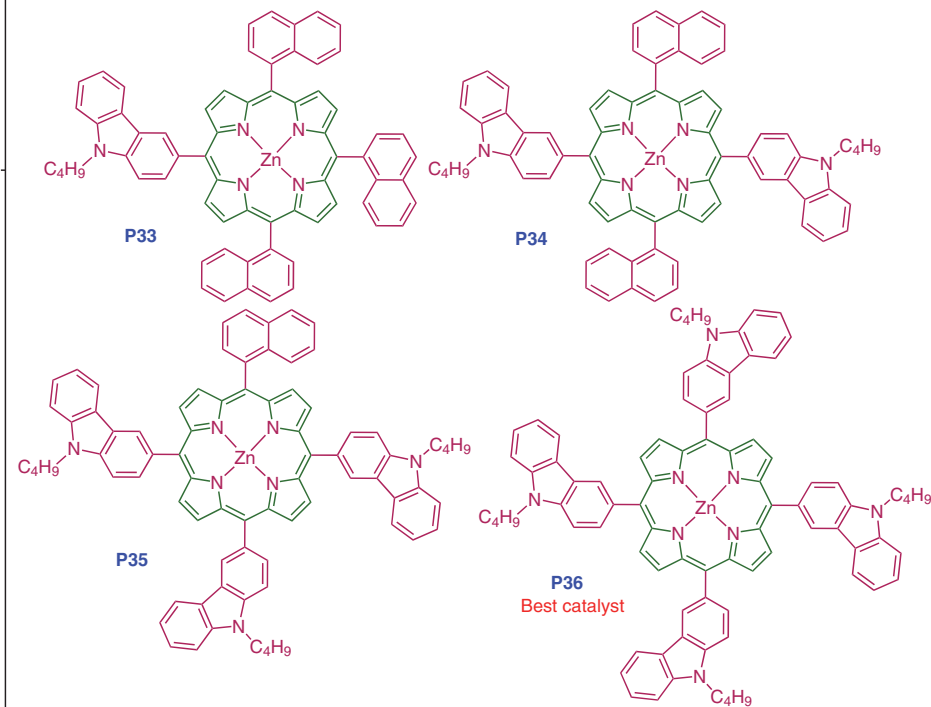
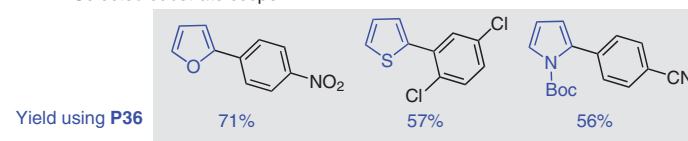
Selected substrate scope

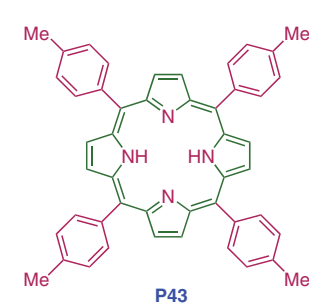
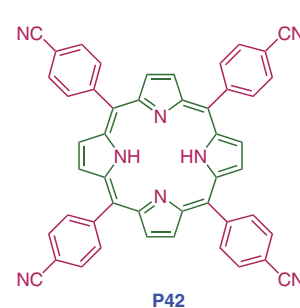
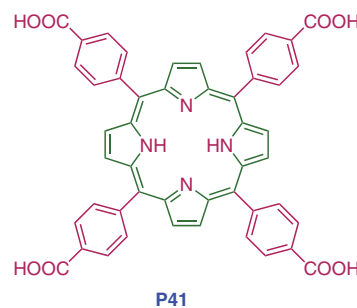
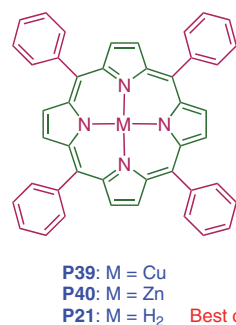
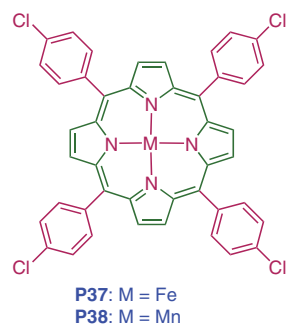
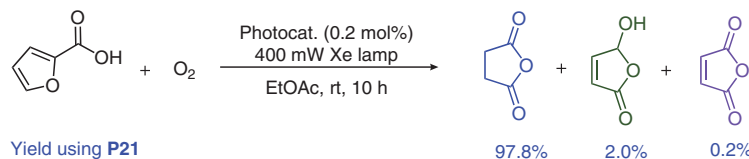
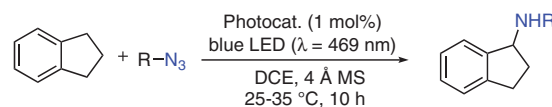
(28) Niu, *J. Mol. Struct.* **2021**, 1237, 130358-130365**Further Reading**

- Related articles on photocatalysis by porphyrins:
- (29) Gryko, *Eur. J. Org. Chem.* **2017**, 2104.
 (30) Oliveira, *Molecules*. **2016**, 21, 310.
 (31) Nam, *J. Porphyrins Phthalocyanines* **2016**, 20, 35.
 (32) Gryko, *J. Am. Chem. Soc.* **2016**, 138, 15451.
 (33) Oliveira, *Beilstein J. Org. Chem.* **2020**, 16, 917.
 (34) Oliveira, *J. Org. Chem.* **2018**, 83, 15077.
 (35) Deyhimi, *Green Chem.* **2011**, 13, 991.
 (36) Safari, *J. Porphyrins Phthalocyanines* **2010**, 14, 639.
 (37) Zhang, *Catal. Sci. Technol.* **2023**, 13, 6132.
 (38) Gryko, *J. Porphyrins Phthalocyanines* **2016**, 20, 76.
 (39) Chan, *Organometallics* **2014**, 33, 7059.

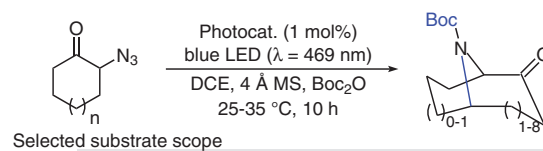
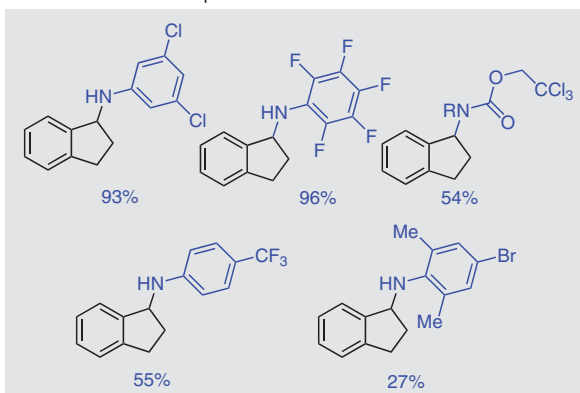
Zinc porphyrins as photoredox catalysts for C–H arylation of heteroarenes⁴⁰


Selected substrate scope

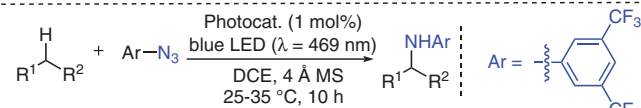
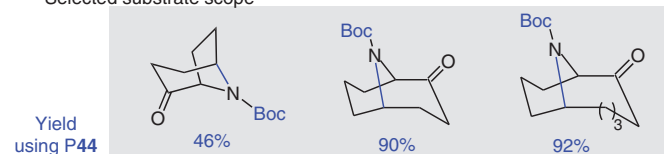
(40) Gupta, *J. Org. Chem.* **2023**, 88, 9424.**Figure 5** Photocatalytic thiocyanation of diketones and indoles and C–H arylation of heteroarenes by porphyrins^{28–40}

Transformation of a furanic compound into succinic anhydride by photosensitizers⁴¹(41) Xue, *iScience* **2023**, 7, 107203.Amination catalyzed by an Fe porphyrin as the photosensitizer⁴²

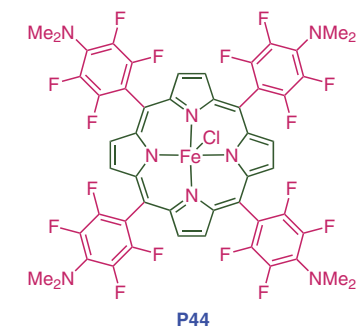
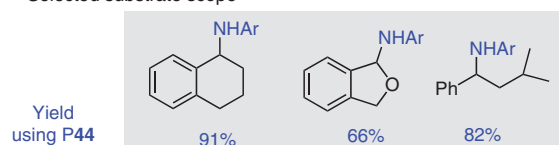
Selected substrate scope

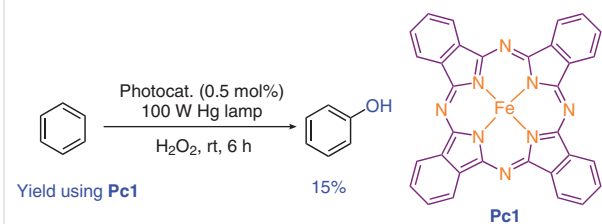
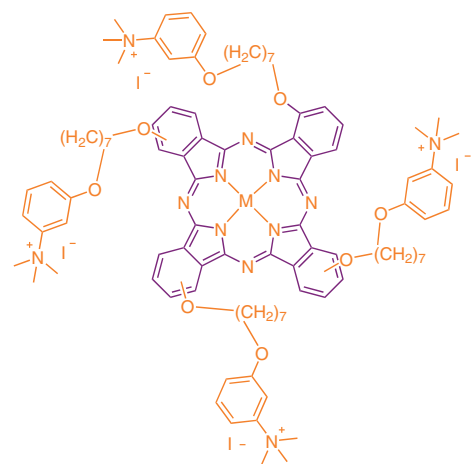
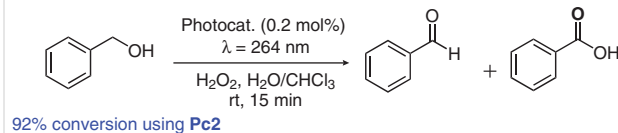


Selected substrate scope



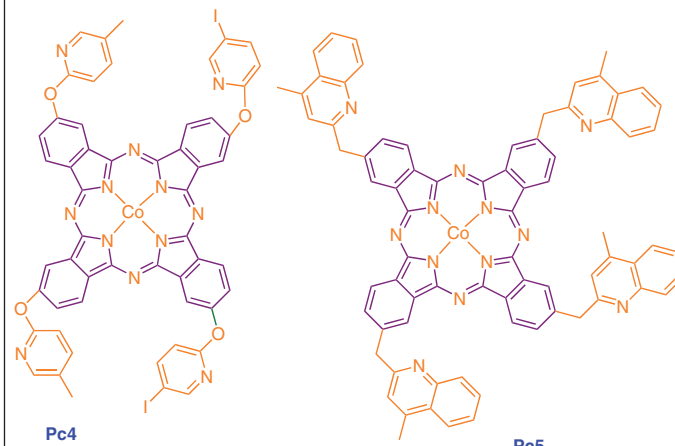
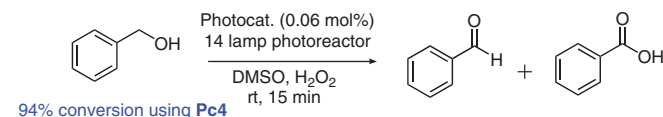
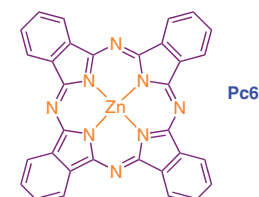
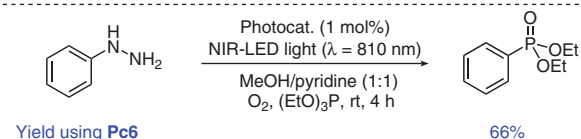
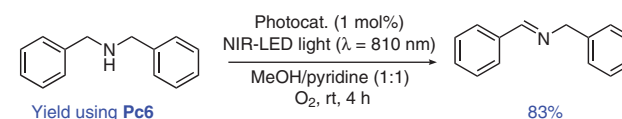
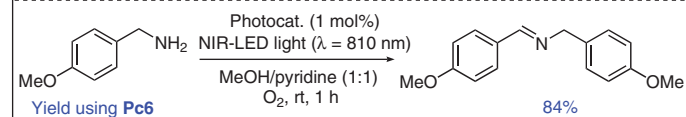
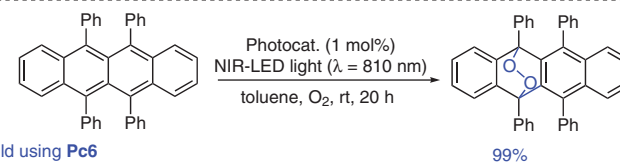
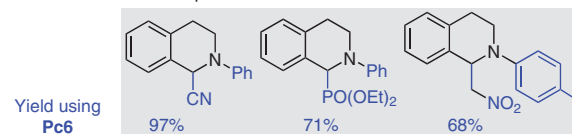
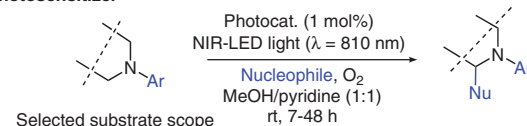
Selected substrate scope

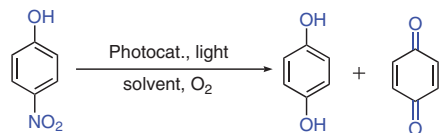
(42) Che, *Chem. Sci.* **2020**, 11, 4680.Figure 6 Photocatalytic oxygenation of a furanic compound, amination and aziridination of alkenes by porphyrins^{41,42}

Photoredox hydroxylation of benzene to phenol⁴³(43) Ghiaci, *J. Photochem. Photobiol. A* **2020**, *392*, 112412.Photo-oxidation of benzylic alcohol by water soluble metallophthalocyanines as photosensitizers⁴⁴(44) Biyiklioglu, *Inorg. Chem. Commun.* **2023**, *158*, 111647.Photophysical properties of phthalocyanine⁴⁵

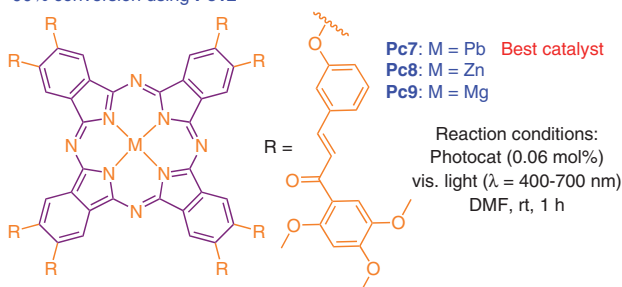
Phthalocyanine in DMF

- $\lambda_{\text{abs}} = 695$ nm, 667 nm, 705 nm
- Fluorescence quantum yield (ϕ_f) = 0.60
- Fluorescence lifetime (τ_f) = 5.25 ns

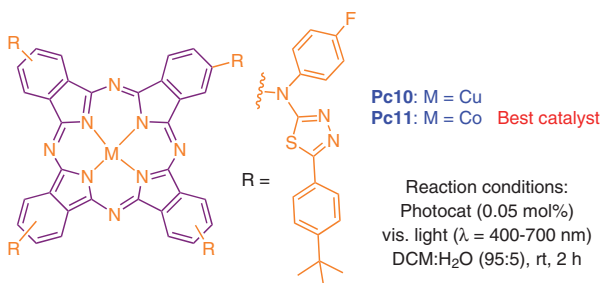
(45) Sahoo, *J. Porphyrin Phthalocyanines* **2003**, *7*, 548-550.Photooxidation of benzyl alcohol by photosensitizers⁴⁶(46) Kantekin, *Appl. Organomet. Chem.* **2023**, *37*, e6975.NIR-light-mediated cross-dehydrogenative coupling (CDC) using zinc phthalocyanine as the photosensitizer⁴⁷(47) Furuyama, *Chem. Eur. J.* **2023**, *28*, e202103223.Figure 7 Photocatalytic hydroxylation of benzene, oxidation of benzylic alcohol and cross-dehydrogenative couplings by phthalocyanines⁴³⁻⁴⁷

Selective photooxidation of nitrophenol using photosensitizers⁴⁸⁻⁵⁰


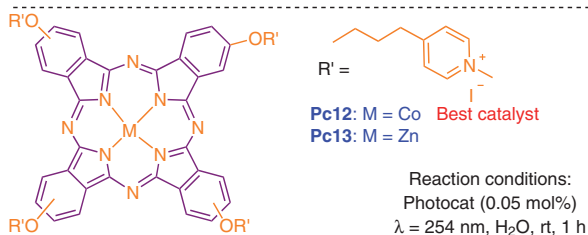
90% conversion using **Pc7**
95% conversion using **Pc11**
90% conversion using **Pc12**



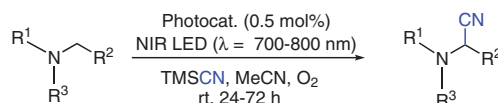
(48) Kantekin, *Inorg. Chem. Commun.* **2020**, *118*, 107998.



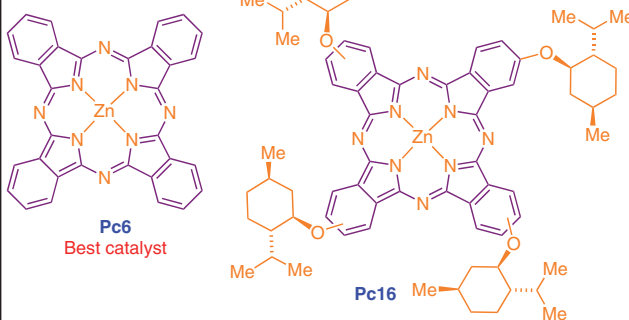
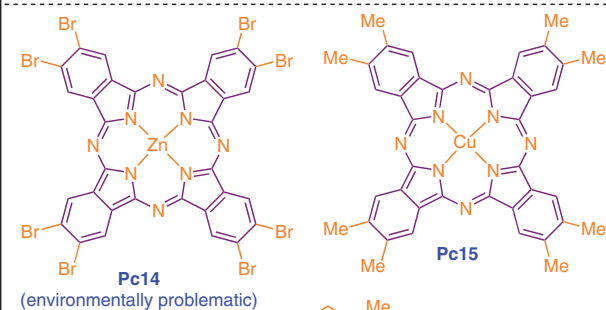
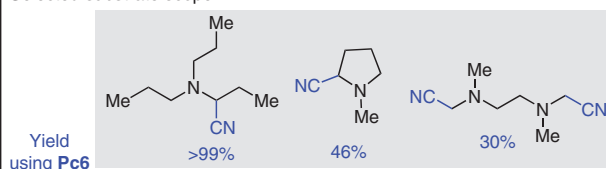
(49) Biyiklioglu, *Inorg. Chim. Acta* **2023**, *547*, 121342.



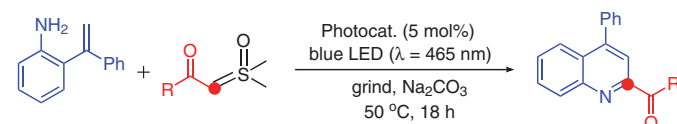
(50) Biyiklioglu, *Polyhedron* **2023**, *243*, 116522.

Cyanation using phthalocyanines as NIR photosensitizers⁵¹


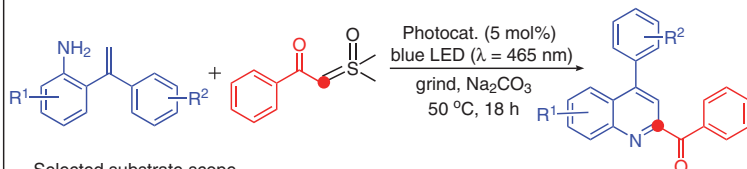
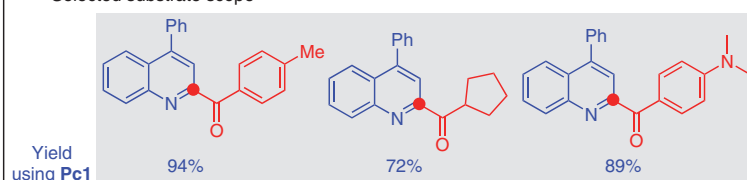
Selected substrate scope



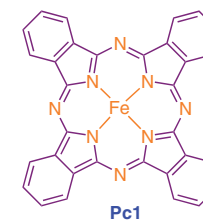
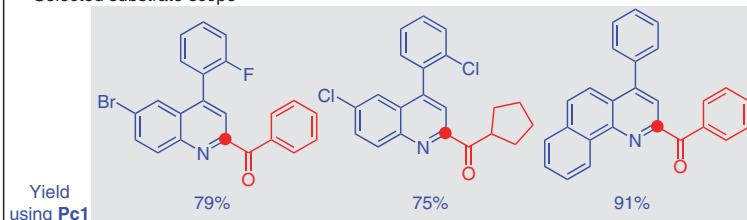
(51) Opatz, *J. Org. Chem.* **2022**, *87*, 5630.

Photo-Thermo-Mechanochemical approach to synthesize quinolones⁵²


Selected substrate scope



Selected substrate scope



(52) Wang, *Org. Lett.* **2022**, *24*, 1146-.

Figure 8 Photocatalytic oxidation of nitrophenol, cyanation of amines and cyclization to quinolones by phthalocyanines⁴⁸⁻⁵²

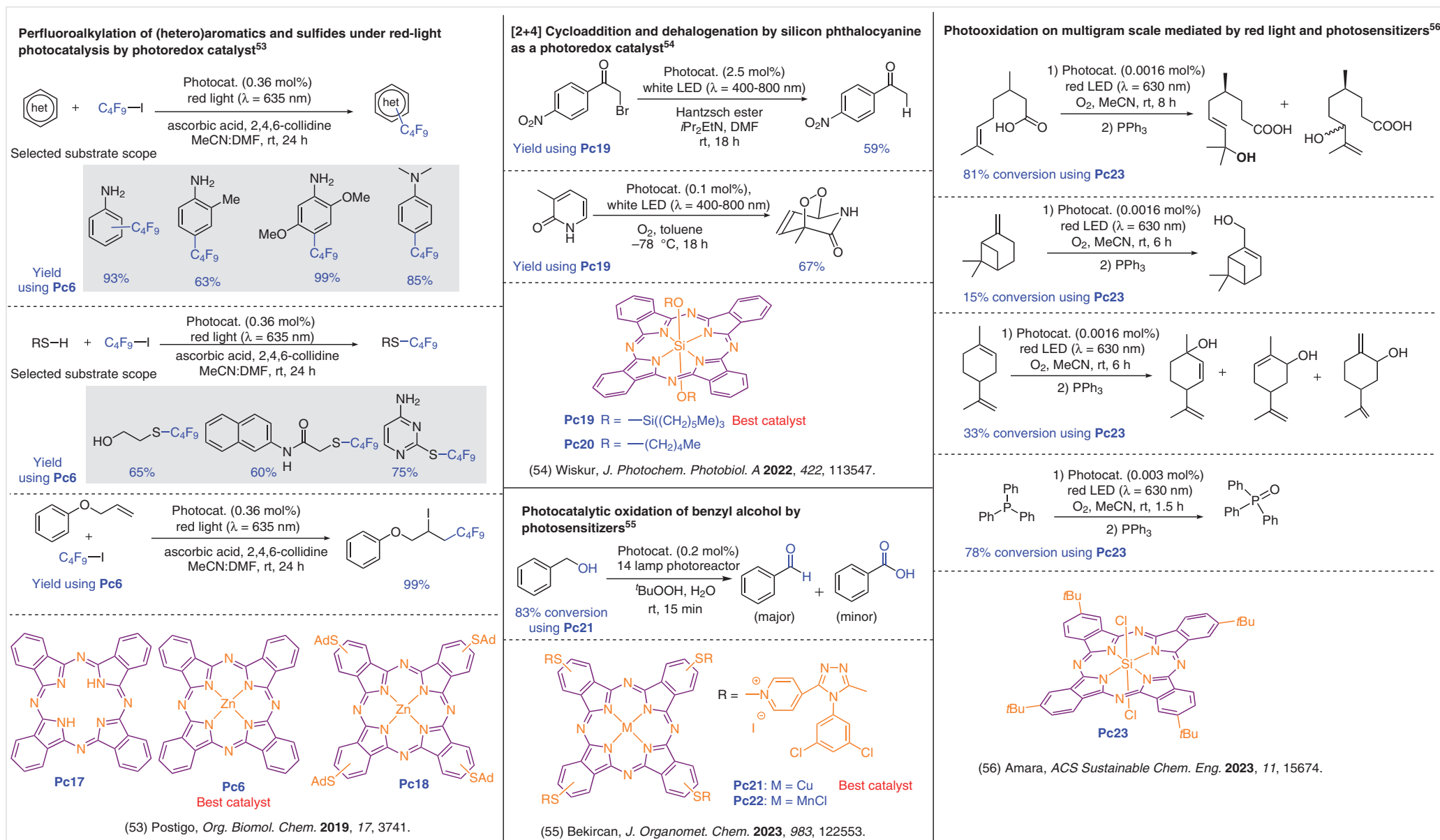
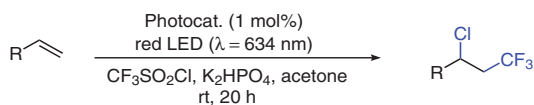
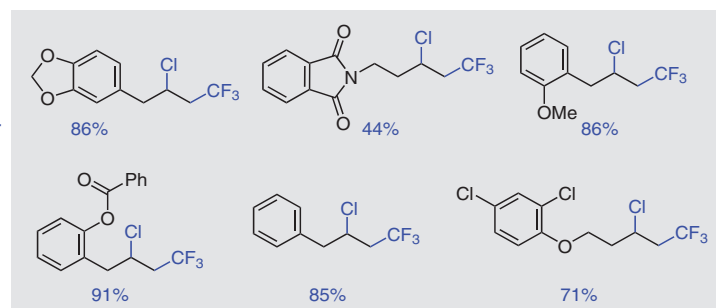
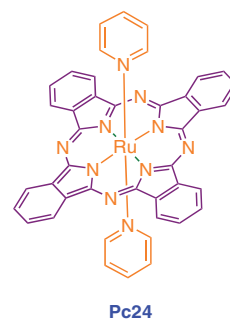
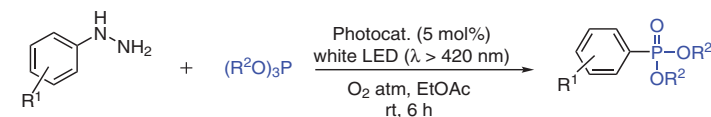


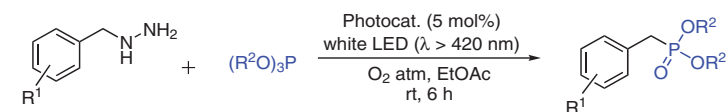
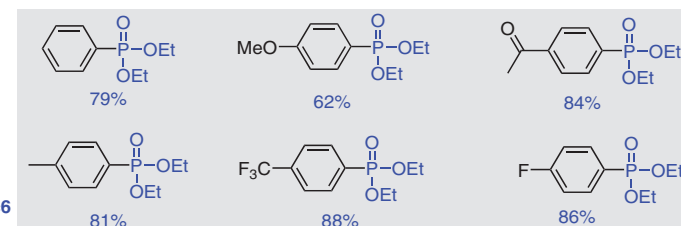
Figure 9 Photocatalytic perfluoroalkylation of aromatics, sulfides and alkenes, cycloaddition and dehalogenation, and oxidation by phthalocyanines^{53–56}

Red-light-mediated chlorotrifluoromethylation of alkenes using a ruthenium phthalocyanine as a photoredox catalyst⁵⁷


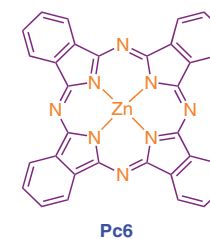
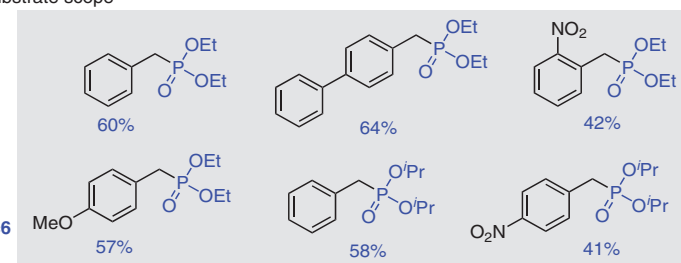
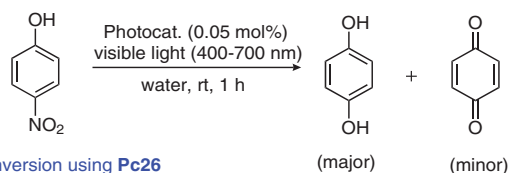
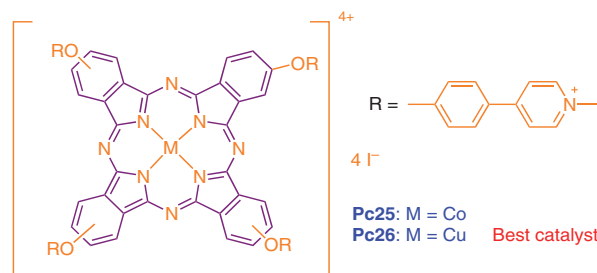
Selected substrate scope

Yield using **Pc24**(57) Furuyama, *Chem. Commun.* **2021**, 57, 13594.
Photocatalytic phosphonylation mediated by zinc phthalocyanine as a photosensitizer⁶⁷


Selected substrate scope

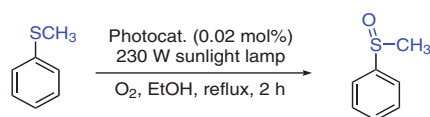
Yield using **Pc6**

Selected substrate scope

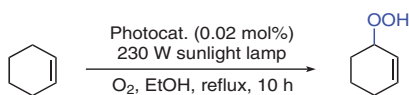
Yield using **Pc6**(67) Sarvari, *Org. Biomol. Chem.* **2021**, 19, 5905.
Photooxidation of 4-nitrophenol in aqueous medium by photosensitizers⁵⁸
97% conversion using **Pc26**(58) Tekintas, *J. Mol. Struct.* **2020**, 1215, 128189.
Further reading

- Related articles on photocatalysis by phthalocyanines:
- (59) Liang, *Curr. Org. Chem.* **2018**, 22, 485.
 - (60) Vorozhtsov, *J. Porphyrin Phthalocyanines* **1999**, 3, 592.
 - (61) Lever, *Adv. Inorg. Chem. Radiochem.* **1965**, 7, 27.
 - (62) Doorslaer, *Dalton Trans.* **2014**, 43, 14942.
 - (63) Nyokong, *J. Mol. Catal. A: Chem.* **2007**, 261, 36.
 - (64) Bilyarska, *J. Mol. Catal. A: Chem.* **1999**, 137, 15.
 - (65) Nyokong, *J. Mol. Struct.* **2010**, 973, 96.
 - (66) Nyokong, *J. Mol. Catal. A: Chem.* **2007**, 273, 149.

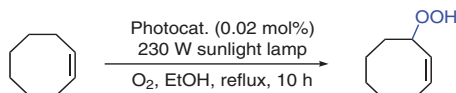
Figure 10 Photocatalytic chlorotrifluoromethylation of alkenes, oxidation of nitrophenol and phosphonylation of hydrazines by phthalocyanines^{57–67}

Photocatalytic aerobic oxygenation reactions catalyzed by antimony corroles as photosensitizers^{8c}

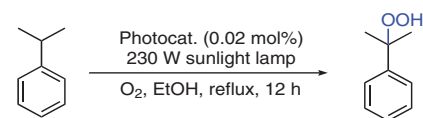
100% conversion using C1



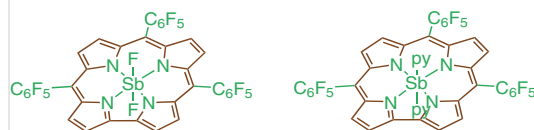
78% conversion using C1



67% conversion using C1

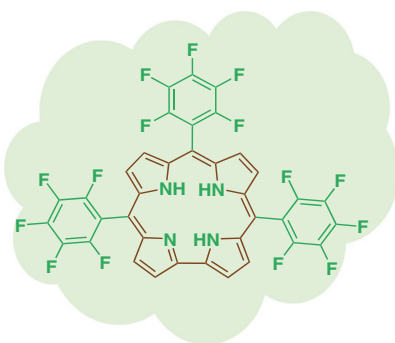


60% conversion using C1

C1
Best catalyst

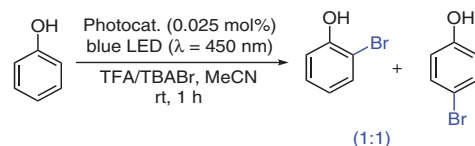
C2

C3

(8c) Gross, *Inorg. Chem.* **2006**, *45*, 386-394.Photophysical properties of corrole⁶⁸

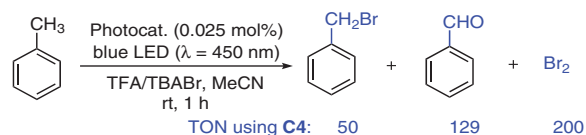
5,10,15-tris(pentafluorophenyl)corrole in DCM

- one Soret and four Q bands in UV-vis spectra
Soret band: 407 nm
Q-bands: 523 nm, 561 nm, 604 nm, 632 nm
- absorption exhibits a high solvent-dependent shift
- Fluorescence quantum yield (ϕ_f) = 0.14
- Fluorescence lifetime (τ_f) = 3.7 ns

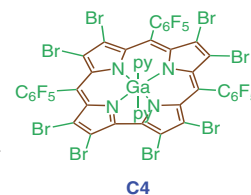
(68) Ziegler, *J. Phys. Chem. A* **2005**, *109*, 7411.Photocatalytic bromination by a gallium corrole photosensitizer⁶⁹

(1:1)

TON using C4: 296



TON using C4: 50 129 200

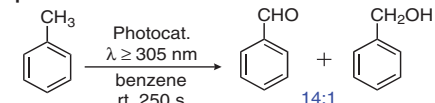


C4

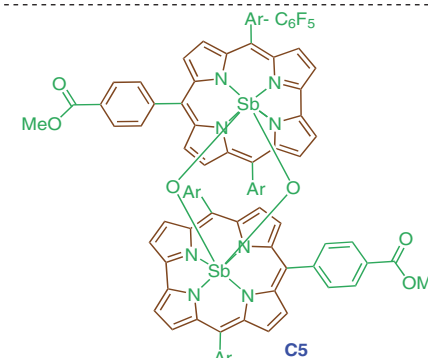
(69) Gross, *Angew. Chem. Int. Ed.* **2015**, *54*, 12547.

Further reading

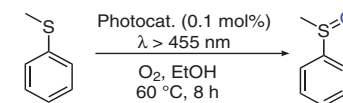
- Related articles on photocatalysis by corroles:
- (70) Gross, *Chem. Eur. J.* **2009**, *15*, 8382.
 - (71) Gross, *Chem. Commun.* **2007**, *20*, 1987.
 - (72) Lemon, *Pure Appl. Chem.* **2020**, *92*, 1901.
 - (73) Gryko, *Eur. J. Org. Chem.* **2002**, *2002*, 1735.
 - (74) Paolesse, *Chem. Soc. Rev.* **2022**, *51*, 1277.
 - (75) Gryko, *Chem. Rev.* **2017**, *117*, 3102.

C-H photoactivation by Sb(V) oxo corrole as photosensitizers⁷⁶

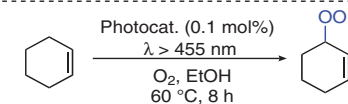
14:1



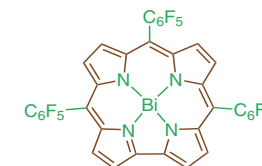
C5

(76) Nocera, *Chem. Commun.* **2020**, *56*, 5247.Oxidation of thioanisole and cyclohexene photocatalyzed by a bismuth corrole as a photosensitizer⁷⁷

Full conversion using C6

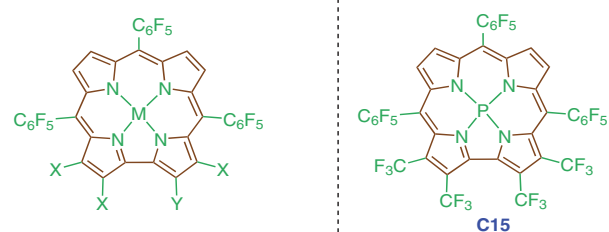
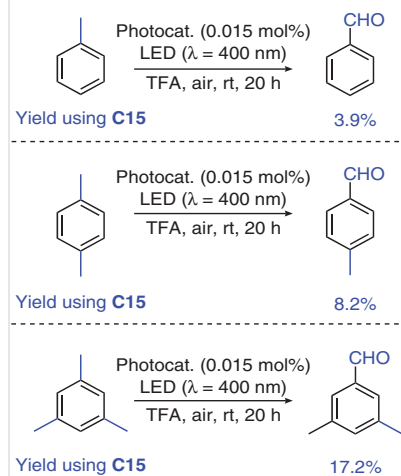


Partial conversion using C6



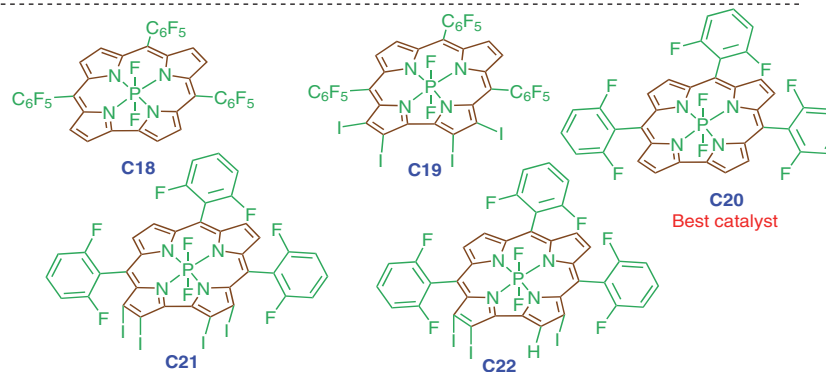
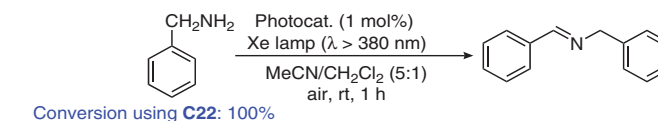
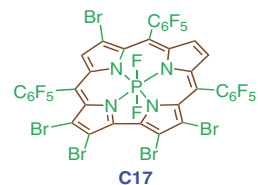
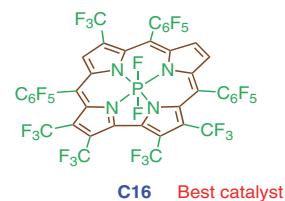
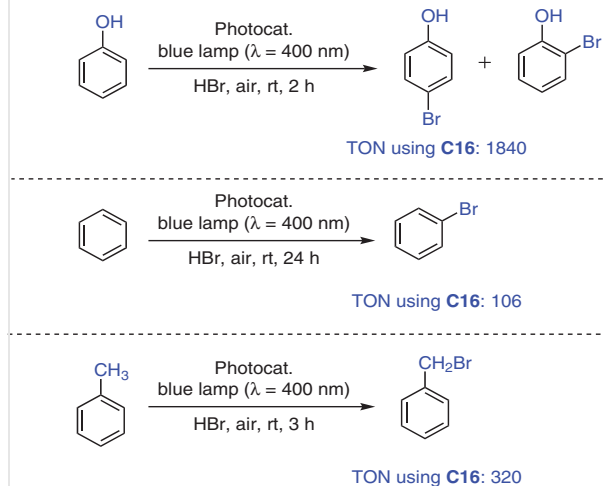
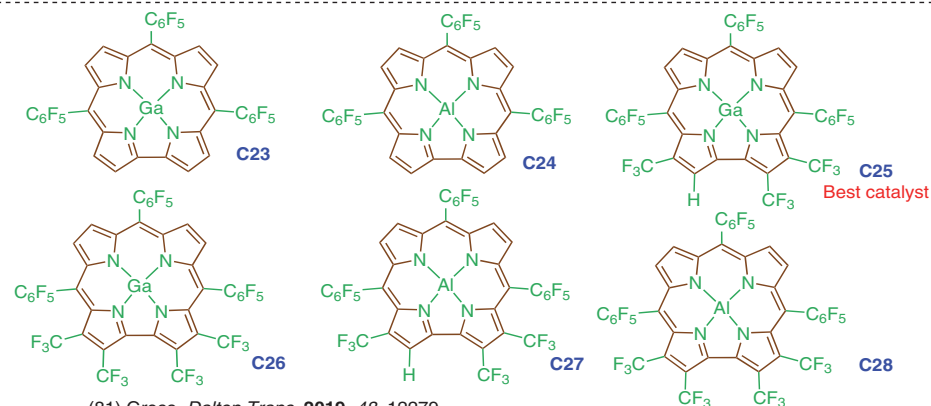
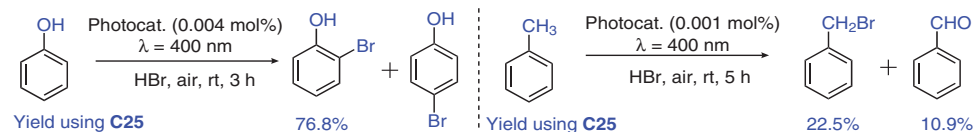
C6

(77) Schoefberger, *Inorg. Chem.* **2011**, *50*, 6788.Figure 11 Photocatalytic oxygenation of thioanisole and alkenes, bromination of phenol and toluene, and oxidation of toluene, thioanisole and cyclohexene by corroles^{8c,68-77}

Photooxygenation of toluene, *p*-xylene and mesitylene by transition-metal- and main-group-metallated corroles as photosensitizers⁷⁸


- C7:** M = Ga, X = CF₃, Y = H
C8: M = Al, X = CF₃, Y = H
C9: M = Au, X = CF₃, Y = H
C10: M = P, X = CF₃, Y = H
C11: M = Co, X = CF₃, Y = H
C12: M = Ga, X = Y = CF₃
C13: M = Al, X = Y = CF₃
C14: M = Au, X = Y = CF₃
C15: M = P, X = Y = CF₃

Best catalyst

(78) Gross, *Photochem. Photobiol. Sci.* **2020**, *19*, 996.
Aza-Henry coupling of benzylamine mediated by phosphorus corroles as photosensitizers⁸⁰
(80) Gross, *Chem. Sci.* **2019**, *10*, 7091.
Photocatalytic bromination of phenol and toluene by phosphorus corroles as photosensitizers⁷⁹
(79) Gross, *Inorg. Chem.* **2019**, *58*, 6184.
Metallocorrole-photocatalyzed bromination of phenol and toluene by photosensitizers⁸¹
(81) Gross, *Dalton Trans.* **2019**, *48*, 12279.
Figure 12 Photocatalytic oxygenation of aromatics, benzylamine coupling and bromination of benzene, phenol and toluene by corroles^{78–81}

Conflict of Interest

The authors declare no conflict of interest.

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References

- Majek, M.; Wangelin, A. J. *Acc. Chem. Res.* **2016**, *49*, 2316.
- Romero, N. A.; Nicewicz, D. A. *Chem. Rev.* **2016**, *116*, 10075.
- Pitre, S. P.; McTiernan, C. D.; Scaiano, J. C. *Acc. Chem. Res.* **2016**, *49*, 1320.
- (a) Crisenza, G. E. M.; Melchiorre, P. *Nat. Commun.* **2020**, *11*, 803. (b) Takeda, H.; Ishitani, O. *Coord. Chem. Rev.* **2010**, *254*, 346. (c) Gratzel, M. *Acc. Chem. Res.* **1981**, *14*, 376. (d) Kalyanasundaram, K.; Gratzel, M. *Chem. Rev.* **1998**, *77*, 347.
- (a) Rueping, M.; Zhu, S.; Koenig, R. M. *Chem. Commun.* **2011**, *47*, 8679. (b) Nguyen, J. D.; Tucker, J. W.; Konieczynska, M. D.; Stephenson, C. R. J. *J. Am. Chem. Soc.* **2011**, *133*, 4160. (c) Ischay, M. A.; Anzovino, M. E.; Du, J.; Yoon, T. P. *J. Am. Chem. Soc.* **2008**, *130*, 12886.
- (a) Millet, A.; Cesana, P. T.; Sedillo, K.; Bird, M. J.; Schlau-Cohen, G. S.; Doyle, A. G.; MacMillan, D. W. C.; Scholes, G. D. *Acc. Chem. Res.* **2022**, *55*, 1423. (b) Chan, A. Y.; Perry, I. B.; Bissonnette, N. B.; Buksh, B. F.; Edwards, G. A.; Frye, L. I.; Garry, O. L.; Lavagnino, M. N.; Li, B. X.; Liang, Y.; Mao, E.; Millet, A.; Oakley, J. V.; Reed, N. L.; Sakai, H. A.; Seath, C. P.; MacMillan, D. W. C. *Chem. Rev.* **2022**, *122*, 1485. (c) Prier, C. K.; Rankic, D. A.; MacMillan, D. W. C. *Chem. Rev.* **2013**, *113*, 5322.
- (a) Majek, M.; Filace, F.; von Wangelin, A. J. *Beilstein J. Org. Chem.* **2014**, *10*, 981. (b) Herbrink, F.; Camarero González, P.; Krstic, M.; Puglisi, A.; Benaglia, M.; Sanz, M. A.; Rossi, S. *Appl. Sci.* **2020**, *10*, 5596.
- (a) Gross, Z.; Simkhovich, L.; Galili, N. *Chem. Commun.* **1999**, 599. (b) Grodkowski, J.; Neta, P.; Fujita, E.; Mahammed, A.; Simkhovich, L.; Gross, Z. *J. Phys. Chem. A* **2022**, *106*, 4772. (c) Luobeznova, I.; Raizman, M.; Goldberg, I.; Gross, Z. *Inorg. Chem.* **2006**, *45*, 386.
- (a) Sorokin, A. B. *Chem. Rev.* **2013**, *113*, 8152. (b) Sorokin, A. B.; Kudrik, E. V. *Catal. Today* **2011**, *159*, 37. (c) Ji, D.; Lu, X.; He, R. *Appl. Catal., A* **2000**, *203*, 329.
- (a) Herreo, C.; Quaranta, A.; Ricoux, R.; Trehoux, A.; Mahammed, A.; Gross, Z.; Banse, F.; Mahy, J.-P. *Dalton Trans.* **2016**, *45*, 706. (b) Gross, Z.; Golubkov, G.; Simkhovich, L. *Angew. Chem. Int. Ed.* **2000**, *39*, 4045.
- Janaagal, A.; Pandey, V.; Sabharwal, S.; Gupta, I. *J. Porphyrins Phthalocyanines* **2021**, *25*, 571.
- Owens, J. W.; Smith, R.; Robinson, R.; Robins, M. *Inorg. Chim. Acta* **1998**, *279*, 226.
- Wasbotten, J. H.; Conradie, J.; Ghosh, A. *J. Phys. Chem. B* **2003**, *107*, 3613.
- Pandey, V.; Jain, D.; Pareek, N.; Gupta, I. *Inorg. Chim. Acta* **2020**, *502*, 119339.
- Pandey, V.; Janaagal, A.; Jain, A.; Mori, S.; Gupta, I. *Dyes Pigm.* **2023**, *209*, 110861.
- Hajimohammadi, M.; Safari, N.; Mofakham, H.; Shaabani, A. *Tetrahedron Lett.* **2010**, *51*, 4061.
- Hajimohammadi, M.; Mofakham, H.; Safari, N.; Manesh, A. M. *J. Porphyrins Phthalocyanines* **2012**, *16*, 93.
- Malone, J.; Klaine, S.; Alcantar, C.; Bratcher, F.; Zhang, R. *New J. Chem.* **2021**, *45*, 4977.
- Capaldo, L.; Ertl, M.; Fagnoni, M.; Knor, G.; Ravelli, D. *ACS Catal.* **2020**, *10*, 9057.
- Shremzer, E. S.; Polivanovskaia, D. A.; Birin, K. P.; Gorbunova, Y. G.; Tsvadze, A. Y. *Dyes Pigm.* **2023**, *210*, 110935.
- Palivanovskaia, D. A.; Abdulaeva, I. A.; Birin, K. P.; Gorbunova, Y. G.; Tsvadze, A. Y. *J. Catal.* **2022**, *413*, 342.
- Yamashita, K.; Sugiura, K. *Tetrahedron Lett.* **2019**, *60*, 151081.
- Zhang, P.; Yu, C.; Yin, Y.; Droste, J.; Klabunde, S.; Hansen, M. R.; Mai, Y. *Chem. Eur. J.* **2020**, *69*, 16497.
- Cheng, Y.; Zhang, Z.; Duan, X.; Zhang, M. *Dalton Trans.* **2022**, *51*, 16517.
- Hong, Y. H.; Han, J. W.; Jung, J.; Nakagawa, T.; Lee, Y.-M.; Nam, W.; Fukuzumi, S. *J. Am. Chem. Soc.* **2019**, *141*, 9155.
- Jasinska, K. R.; Wdowik, T.; Łuczak, K.; Wierzba, A. J.; Drapala, O.; Gryko, D. *ACS Org. Inorg. Au* **2022**, *2*, 422.
- Wang, H. H.; Shao, H.; Huang, G.; Fan, J.; To, W. P.; Dang, L.; Liu, Y.; Che, C. M. *Angew. Chem. Int. Ed.* **2023**, *62*, e202303981.
- Yu, X. Y.; Su, H.; Zheng, X.; Liu, W. B.; He, Y.; Fei, N. N.; Qiao, R.; Ren, Y. L.; Niu, C. Y. *J. Mol. Struct.* **2021**, *1237*, 130358.
- Jasinska, K. R.; König, B.; Gryko, D. *Eur. J. Org. Chem.* **2017**, 2104.
- Castano, J. C. B.; Carmona-Vargas, C. C.; Brckson, T. J.; Oliveira, K. T. *Molecules* **2016**, *21*, 310.
- Fukuzumi, S.; Nam, W. *J. Porphyrins Phthalocyanines* **2016**, *20*, 35.
- Jasinska, K.; Shan, W.; Zawada, K.; Kadish, K. M.; Gryko, D. *J. Am. Chem. Soc.* **2016**, *138*, 15451.
- Silva, R. C.; Silva, L. O.; Bartolomeu, A. D. A.; Brocksom, T. J.; Oliveira, K. T. *Beilstein J. Org. Chem.* **2020**, *16*, 917.
- Souza, A. A. N.; Silva, N. S.; Muller, A. V.; Polo, A. S.; Brocksom, T. J.; Oliveira, K. T. *J. Org. Chem.* **2018**, *83*, 15077.
- Hajimohammadi, M.; Safari, N.; Mofakham, H.; Deyhimi, F. *Green Chem.* **2011**, *13*, 991.
- Hajimohammadi, M.; Safari, N. *J. Porphyrins Phthalocyanines* **2010**, *14*, 639.
- Gao, X.; Tong, X.; Liu, R.; Zhang, Y. *Catal. Sci. Technol.* **2023**, *13*, 6132.
- Jasinska, K. R.; Ciszewski, L. W.; Gryko, D. T.; Gryko, D. *J. Porphyrins Phthalocyanines* **2016**, *20*, 76.
- Li, B. Z.; Qian, Y. Y.; Liu, J.; Chan, K. S. *Organometallics* **2014**, *33*, 7059.
- Janaagal, A.; Sanyam, ; Mondal, A.; Gupta, I. *J. Org. Chem.* **2023**, *88*, 9424.
- Gao, X.; Tong, X.; Zhang, Y.; Xue, S. *iScience* **2023**, *7*, 107203.
- Du, Y. D.; Zhou, C. Y.; To, W. P.; Wang, H. X.; Che, C. M. *Chem. Sci.* **2020**, *11*, 4680.
- Asghari, S.; Farahmand, S.; Razavizadeh, J. S.; Ghiaci, M. *J. Photochem. Photobiol., A* **2020**, *392*, 112412.
- Ozturmen, B. A.; Akkol, C.; Saka, E. T.; Biyiklioglu, Z. *Inorg. Chem. Commun.* **2023**, *158*, 111647.
- Chauhan, S. M. S.; Srinivas, K. A.; Srivastava, P. K.; Sahoo, B. *J. Porphyrins Phthalocyanines* **2003**, *7*, 548.
- Yalazan, H.; Akkol, C.; Saka, E. T.; Kantekin, H. *Appl. Organomet. Chem.* **2023**, *37*, e6975.
- Katsurayama, Y.; Ikabata, Y.; Maeda, H.; Segi, M.; Nakai, H.; Furuyama, T. *Chem. Eur. J.* **2023**, *28*, e202103223.
- Yalazan, H.; Tekintas, K.; Serdaroglu, V.; Saka, E. T.; Kahriman, N.; Kantekin, H. *Inorg. Chem. Commun.* **2020**, *118*, 107998.
- Saka, E. T.; Tekintas, K.; Bekircan, O.; Biyiklioglu, Z. *Inorg. Chim. Acta* **2023**, *547*, 121342.
- Saka, E. T.; Cakmak, U.; Akkol, C.; Biyiklioglu, Z. *Polyhedron* **2023**, *243*, 116522.
- Grundke, C.; Silva, R. C.; Kitzmann, W. R.; Heinze, K.; Oliveira, K. T.; Opatz, T. *J. Org. Chem.* **2022**, *87*, 5630.
- Liu, L.; Lin, J.; Pang, M.; Jin, H.; Yu, X.; Wang, S. *Org. Lett.* **2022**, *24*, 1146.
- Yerien, D. E.; Cooke, M. V.; Vior, M. C. G.; Vallejo, S. B.; Postigo, A. *Org. Biomol. Chem.* **2019**, *17*, 3741.
- Dickerson, S. D.; Ayare, P. J.; Vannucci, A. K.; Wiskur, S. L. *J. Photochem. Photobiol., A* **2022**, *422*, 113547.
- Fazli, H.; Akkol, C.; Osmanogullari, S. C.; Bekircan, O. *J. Organomet. Chem.* **2023**, *983*, 122553.

- (56) Lancel, M.; Golisano, T.; Monnereau, C.; Gomez, C.; Port, M.; Amara, Z. *ACS Sustainable Chem. Eng.* **2023**, *11*, 15674.
- (57) Ishikawa, Y.; Kameyama, T.; Torimoto, T.; Maeda, H.; Segi, M.; Furuyama, T. *Chem. Commun.* **2021**, *57*, 13594.
- (58) Saka, E. T.; Tekintas, K. *J. Mol. Struct.* **2020**, *1215*, 128189.
- (59) Chen, J.; Zhu, C.; Xu, Y.; Zhang, P.; Liang, T. *Curr. Org. Chem.* **2018**, *22*, 485.
- (60) Laliya, O. K.; Lukyanets, E. A.; Vorozhtsov, G. N. *J. Porphyrins Phthalocyanines* **1999**, *3*, 592.
- (61) Lever, A. B. P. *Adv. Inorg. Chem. Radiochem.* **1965**, *7*, 27.
- (62) Moons, H.; Loas, A.; Gorun, S. M.; Doorslaer, S. V. *Dalton Trans.* **2014**, *43*, 14942.
- (63) Marais, E.; Klein, R.; Antunes, E.; Nyokong, T. *J. Mol. Catal. A: Chem.* **2007**, *261*, 36.
- (64) Iliev, V.; Bilyarska, V. A. *J. Mol. Catal. A: Chem.* **1999**, *137*, 15.
- (65) Ogunbayo, T. B.; Nyokong, T. *J. Mol. Struct.* **2010**, *973*, 96.
- (66) Tau, P.; Nyokong, T. *J. Mol. Catal. A: Chem.* **2007**, *273*, 149.
- (67) Koohgard, M.; Sarvari, M. H. *Org. Biomol. Chem.* **2021**, *19*, 5905.
- (68) Ding, T.; Aleman, E. A.; Modarelli, D. A.; Ziegler, C. J. *J. Phys. Chem. A* **2005**, *109*, 7411.
- (69) Mahammed, A.; Gross, Z. *Angew. Chem. Int. Ed.* **2015**, *54*, 12547.
- (70) Harel, I. A.; Gross, Z. *Chem. Eur. J.* **2009**, *15*, 8382.
- (71) Aviv, I.; Gross, Z. *Chem. Commun.* **2007**, *20*, 1987.
- (72) Lemon, C. M. *Pure Appl. Chem.* **2020**, *92*, 1901.
- (73) Gryko, D. T. *Eur. J. Org. Chem.* **2002**, 1735.
- (74) Natale, C. D.; Gros, C. P.; Paolesse, R. *Chem. Soc. Rev.* **2022**, *51*, 1277.
- (75) Orłowski, R.; Gryko, D.; Gryko, D. T. *Chem. Rev.* **2017**, *117*, 3102.
- (76) Lemon, C. M.; Maher, A. G.; Mazzotti, A. R.; Powers, D. C.; Gonzalez, M. I.; Nocera, D. G. *Chem. Commun.* **2020**, *56*, 5247.
- (77) Reith, L. M.; Stiftinger, M.; Monkowius, U.; Knor, G.; Schoefberger, W. *Inorg. Chem.* **2011**, *50*, 6788.
- (78) Zhan, X.; Kolanu, S.; Fite, S.; Chen, Q. C.; Lee, W.; Churchill, D. G.; Gross, Z. *Photochem. Photobiol. Sci.* **2020**, *19*, 996.
- (79) Zhan, X.; Teplitzky, P.; Posner, Y. D.; Sundararajan, M.; Ullah, Z.; Chen, Q. C.; Shimon, L. J. W.; Saltsman, I.; Mahammed, A.; Kosa, M.; Baik, M. H.; Churchill, D. G.; Gross, Z. *Inorg. Chem.* **2019**, *58*, 6184.
- (80) Mahammed, A.; Chen, K.; Vestfrid, J.; Zhao, J.; Gross, Z. *Chem. Sci.* **2019**, *10*, 7091.
- (81) Zhan, X.; Yadav, P.; Posner, Y. D.; Fridman, N.; Sundararajan, M.; Ullah, Z.; Chen, Q. C.; Shimon, L. J. W.; Mahammed, A.; Churchill, D. G.; Baik, M. H.; Gross, Z. *Dalton Trans.* **2019**, *48*, 12279.