Supporting information

Mirror, mirror on the wall which is the greenest of them all? A critical comparison of chemo- and biocatalytic oxyfunctionalisation reactions

Yinqi Wu,[a] Caroline E. Paul,[a] and Frank Hollmann,[a]*

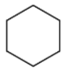
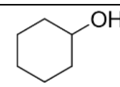
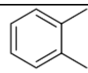
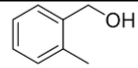
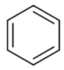
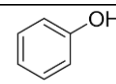
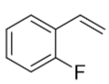
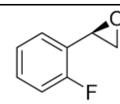
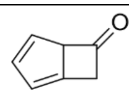
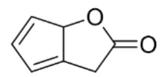
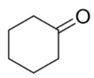
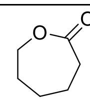
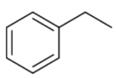
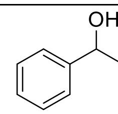
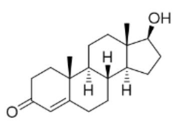
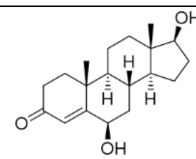
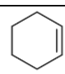
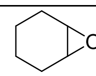
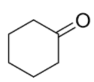
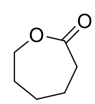
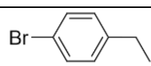
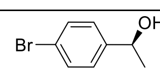
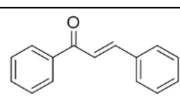
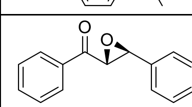
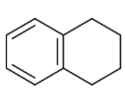
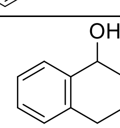
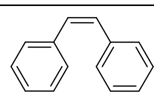
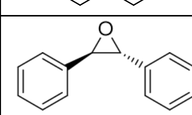
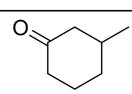
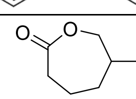
[a] Department of Biotechnology, Delft University of Technology, van der Maasweg 9, 2629 HZ Delft, The Netherlands

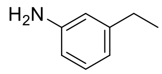
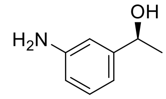
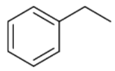
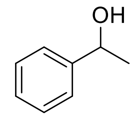
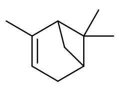
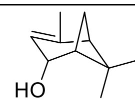
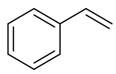
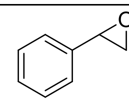
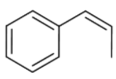
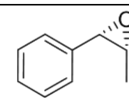
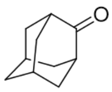
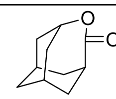
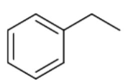
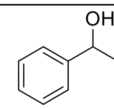
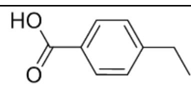
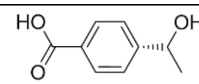
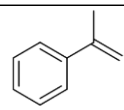
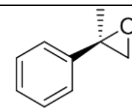
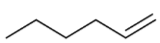
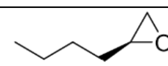
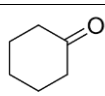
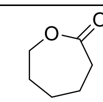
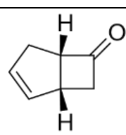
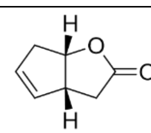
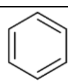
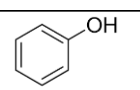
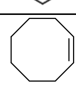
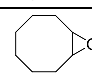
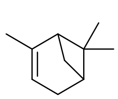
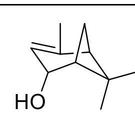
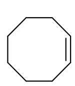
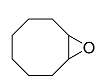
*Corresponding author, e-mail: F.Hollmann@tudelft.nl

Contents

1. Supporting tables

Table S1. Some selected examples of different oxidants used in oxyfunctionalisation reactions.

Oxidant	Substrate	[Oxidant] / [Substrate]	Catalyst	Product	TON	ref
H_2O_2		5	$[Co^{III}_4 Fe^{III}_2 O(L^{10})_8]$ 4DMF·H_2O		3600	1
H_2O_2		1.33	*Cfu*CPO		43000	2
H_2O_2		1	$[Cu(tmpa)]^{2+}$/Al-MCM-41		4320	3
H_2O_2		20	P450BM3 variant (F87A/T268A/V78A/A184L)		3480	4
H_2O_2		1	(*R*,*R*)-*N*,*N*'-bis(3,5-di-*tert*-butylsalicylidene)-1,2-cyclohexanediamino-Co(II)		60	5
H_2O_2		4000	CALB variant S105A		1.57	6
PhIO		0.1	Vaulted binaphthyl metalloporphyrins		400	7
PhIO		1	CYP2A		-	8
PhIO		0.05	$[Mn^{III}(TDCPP)Cl]$		22.5	9
PhIO		0.04	$[Fe^{II}(CH_3CN)($ *N*,*N*-bis(2-pyridylmethyl)-*N*-bis(2-pyridyl)methyl-amine$)(ClO_4)]ClO_4$		-	10
$PhI(OAc)_2$		0.1	Fe^{III} porphyrin complex		67.4	11
$PhI(OAc)_2$		1.5	$[Mn(^{R}peb)(OTf)_2]$		172	12
m-CPBA		0.1	$Fe^{III}_2(O)(L)(OBz)](ClO_4)$		98	13
m-CPBA		0.1	$[Ni^{II}(L^9)Cl]$		24	14
m-CPBA		0.5	L-RaPr$_2$-*t*Bu/Sc$(OTf)_3$		1.76	15

tert-butanol		-	EbDH		-	16
TBHP		5	[((*R*)-(−)-N4Py*)$Fe^{II}(CH_3CN)]^{2+}$		105	17
TBHP		0.0002	*Aae*UPO		-	18
TBHP		2.0	MnO_2 NP/g-C_3N_4		-	19
TBHP		0.01	Imm-*Aae*UPO		96000	20
TBHP		2	Sn–Y zeolite		-	21
O_2 (air)		-	Mn^{II}-Met@MMNPs		6235	22
O_2 (air)		-	CYP199A4		5400	23
O_2 (air)		-	Fe_3O_4-[Mn(TCPP-Ind)Cl]		142857	24
O_2 (air)		-	*Rh*SMO		-	25
O_2 (air)		-	mSiO_2-500		-	26
O_2 (air)		-	*Pp*BVMO variant Y160H		2000	27
H_2O		-	mTiO_2(61)		0.01	28
H_2O		-	$RuO_2/N_{0.12}C$		-	29
UHP		0.0002	*Aae*UPO		-	18
UHP		1.4	Mn^{III} complex		70	30

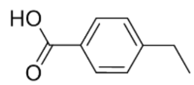
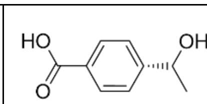
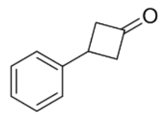
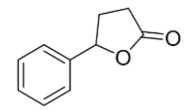
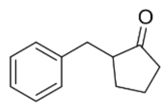
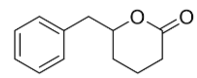
UHP		16-320	CYP199A4			31
UHP		1.3	$(PhCN)_2PdCl$		19.4	32
UHP		8.2	CalB		149	33

Table S2. Abbreviation list.

Al	aluminium	ZEP	zeaxanthin epoxidase
Sc	scandium	XiaF	indosespene 3-hydroxylase
Ti	titanium	IBAH	isobutylamine N1-monooxygenase
V	vanadium	RubN8	dTDP-L-evernosamine N-hydroxylase
Mn	manganese	DnmZ	dTDP-L-epivancosamine N-hydroxylase
Fe	iron	KijD3	dTDP-3-amino-2,3,6-trideoxy-4-keto-3-methyl-D-glucose N-hydroxylase
Ni	nickel	RIFMO	rifampicin monooxygenase
Co	cobalt	LUX	luciferase
Cu	copper	DKCMO	diketocamphane monooxygenase
Se	selenium	LadA	long-chain alkane-degrading monooxygenase
Zr	zirconium	3HB4H	3-hydroxybenzoate 4-hydroxylase
Mo	molybdenum	HbpA	2-hydroxybiphenyl 3-monooxygenase
Ru	ruthenium	TropB	3-methylorcinaldehyde monooxygenase
Pt	platinum	Mab3	3-aminobenzoate 6-hydroxylase
Sn	tin	3HB6H	3-hydroxybenzoate 6-hydroxylase
Re	rhenium	Ubi	2-polyprenylphenol 6-hydroxylase
TBHP	*tert*-butyl hydroperoxide	PHBH	4-hydroxybenzoate 3-hydroxylase
H_2O_2	hydrogen peroxide	HPAH	4-hydroxyphenylacetate 3- hydroxylase
PhIO	iodosobenzene	TsrE	2-methyl-indolylpyruvate 3-hydroxylase
Si	silicon	VCPO	vanadium chloroperoxidase
P	phosphorus	AMO	ammonia monooxygenase
FPMO	flavoprotein monooxygenase	LPMO	lytic polysaccharide monooxygenase
P450	cytochrome P450 monooxygenase	TON	turnover number
UPO	unspecific peroxygenase	CPO	chloroperoxidase from *Caldariomyces fumago*
αKAO	α-keto acid dependent oxygenase	CH_2Cl_2	dichloromethane
PAH	phenylalanine hydroxylase	$CHCl_3$	chloroform
TH	tyrosine hydroxylase	MeCN	acetonitrile
TPH	tryptophan hydroxylase	2LPS	two-aqueous-phase
AH	amino acid hydrolase (PAH, TH, TPH)	imm-*Aae*UPO PaDa-I	immobilized UPO from *Agrocybe aegerita*
BDO	benzene dioxygenase	NaOH	sodium hydroxide
TDO	toluene dioxygenase	Et_2O	diethyl ether
BPDO	biphenyl dioxygenase	UHP	hydrogen peroxide-urea
CDO	chlorobenzene dioxygenase	*m*-CPBA	*m*-chloroperoxybenzoic acid

BZDO	benzoic acid dioxygenase	$PhI(OAc)_2$	iodobenzene diacetate
NBDO	nitrobenzene dioxygenase	EbDHs	ethylbenzene hydroxylases
NDO	naphthalene dioxygenase	K	ketone product formed in the hydroxylation
BLDO	benzylic dioxygenase (BDO, TDO, BPDO, CDO, BZDO, NBDO, NDO)	A	alcohol product formed in the hydroxylation
CPO	haloperoxidase	Ar	argon
VAO	vanillyl-alcohol oxidase	SMOs	styrene monooxygenases
XOR	xanthine oxidoreductase	NL	normal product formed in the Baeyer-Villiger oxidation
NAH	nicotinic acid hydroxylase	AL	abnormal product formed in the Baeyer-Villiger oxidation
IMO	indole monooxygenase	BVMO	Baeyer-Villiger monooxygenase
PhqK	spirocycle-forming monooxygenase	CALB	lipase B from *Candida antarctica*,
MtmOIV	premithramycin B monooxygenase	$CDCl_3$	deuterated chloroform
H3H	hispidin 3-hydroxylase	SDS	sodium dodecyl sulfate
SQLE	squalene epoxidase		

Table S3. Selected oxyfunctionalisation reactions catalysed by chemocatalysts and biocatalysts

Comparison of parameters in selected reactions could be found in the attached excel file.

2. References

1. Nesterov, D. S.; Chygorin, E. N.; Kokozay, V. N.; Bon, V. V.; Boča, R.; Kozlov, Y. N.; Shul'pina, L. S.; Jezierska, J.; Ozarowski, A.; Pombeiro, A. J., Heterometallic CoIII4FeIII2 Schiff base complex: structure, electron paramagnetic resonance, and alkane oxidation catalytic activity. *Inorg. Chem.* **2012,** *51* (16), 9110-9122.

2. Park, J. B.; Clark, D. S., Deactivation mechanisms of chloroperoxidase during biotransformations. *Biotechnol. Bioeng.* **2006,** *93* (6), 1190-1195.

3. Yamada, M.; Karlin, K. D.; Fukuzumi, S., One-step selective hydroxylation of benzene to phenol with hydrogen peroxide catalysed by copper complexes incorporated into mesoporous silica–alumina. *Chem. Sci.* **2016,** *7* (4), 2856-2863.

4. Zhao, P.; Chen, J.; Ma, N.; Chen, J.; Qin, X.; Liu, C.; Yao, F.; Yao, L.; Jin, L.; Cong, Z., Enabling highly (R)-enantioselective epoxidation of styrene by engineering unique non-natural P450 peroxygenases. *Chem. Sci.* **2021,** *12* (18), 6307-6314.

5. Bianchini, G.; Cavarzan, A.; Scarso, A.; Strukul, G., Asymmetric Baeyer–Villiger oxidation with Co (Salen) and H 2 O 2 in water: striking supramolecular micelles effect on catalysis. *Green Chem.* **2009,** *11* (10), 1517-1520.

6. Wang, X.-P.; Zhou, P.-F.; Li, Z.-G.; Yang, B.; Hollmann, F.; Wang, Y.-H., Engineering a lipase B from Candida antactica with efficient perhydrolysis performance by eliminating its hydrolase activity. *Sci. Rep.* **2017,** *7* (1), 1-5.

7. Groves, J. T.; Viski, P., Asymmetric hydroxylation, epoxidation, and sulfoxidation catalyzed by vaulted binaphthyl metalloporphyrins. *J. Org. Chem.* **1990,** *55* (11), 3628-3634.

8. Strohmaier, S. J.; Baek, J. M.; De Voss, J. J.; Jurva, U.; Andersson, S.; Gillam, E. M., An inexpensive, efficient alternative to NADPH to support catalysis by thermostable cytochrome P450 enzymes. *ChemCatChem* **2020,** *12* (6), 1750-1761.

9. Guo, M.; Lee, Y.-M.; Seo, M. S.; Kwon, Y.-J.; Li, X.-X.; Ohta, T.; Kim, W.-S.; Sarangi, R.; Fukuzumi, S.; Nam, W., Mn (III)-Iodosylarene Porphyrins as an Active Oxidant in Oxidation Reactions: Synthesis, Characterization, and Reactivity Studies. *Inorg. Chem.* **2018,** *57* (16), 10232-10240.
10. Lakk-Bogáth, D.; Speier, G.; Kaizer, J., Oxoiron (iv)-mediated Baeyer–Villiger oxidation of cyclohexanones generated by dioxygen with co-oxidation of aldehydes. *New J. Chem.* **2015,** *39* (11), 8245-8248.
11. Le Maux, P.; Srour, H. F.; Simonneaux, G., Enantioselective water-soluble iron–porphyrin-catalyzed epoxidation with aqueous hydrogen peroxide and hydroxylation with iodobenzene diacetate. *Tetrahedron* **2012,** *68* (29), 5824-5828.
12. Tian, J.; Lin, J.; Zhang, J.; Xia, C.; Sun, W., Asymmetric Epoxidation of Olefins Catalyzed by Substituted Aminobenzimidazole Manganese Complexes Derived from L‐Proline. *Adv. Synth. Catal.* **2022,** *364* (3), 593-600.
13. Nagataki, T.; Tachi, Y.; Itoh, S. J. J. o. M. C. A. C., Synthesis, characterization, and catalytic oxygenation activity of dinuclear iron (III) complex supported by binaphthol-containing chiral ligand. *J. Mol. Catal. A Chem.* **2005,** *225* (1), 103-109.
14. Nesterov, D. S.; Nesterova, O. V., Catalytic Oxidations with Meta-Chloroperoxybenzoic Acid (m-CPBA) and Mono-and Polynuclear Complexes of Nickel: A Mechanistic Outlook. *Catalysts* **2021,** *11* (10), 1148.
15. Wu, W.; Cao, W.; Hu, L.; Su, Z.; Liu, X.; Feng, X., Asymmetric Baeyer–Villiger oxidation: classical and parallel kinetic resolution of 3-substituted cyclohexanones and desymmetrization of meso-disubstituted cycloketones. *Chem. Sci.* **2019,** *10* (29), 7003-7008.
16. Dudzik, A.; Kozik, B.; Tataruch, M.; Wójcik, A.; Knack, D.; Borowski, T.; Heider, J.; Witko, M.; Szaleniec, M., The reaction mechanism of chiral hydroxylation of p-OH and p-NH2 substituted compounds by ethylbenzene dehydrogenase. *Can. J. Chem.* **2013,** *91* (9), 775-786.
17. Lakk-Bogáth, D.; Kripli, B.; Meena, B. I.; Speier, G.; Kaizer, J., Catalytic and stoichiometric CH oxidation of benzylalcohols and hydrocarbons mediated by nonheme oxoiron (IV) complex with chiral tetrapyridyl ligand. *Inorg. Chem. Commun.* **2019,** *104*, 165-170.
18. Negoi, A.; Parvulescu, V. I.; Tudorache, M., Peroxidase-based biocatalysis in a two-phase system for allylic oxidation of α-pinene. *Catal. Today* **2018,** *306*, 199-206.
19. Zhang, Y.; Li, H.; Zhang, L.; Gao, R.; Dai, W.-L.; Engineering, Construction of highly efficient 3D/2D MnO2/g-C3N4 nanocomposite in the epoxidation of styrene with TBHP. *ACS Sustain. Chem. Eng.* **2019,** *7* (20), 17008-17019.
20. Nintzel, F. E.; Wu, Y.; Planchestainer, M.; Held, M.; Alcalde, M.; Hollmann, F., An alginate-confined peroxygenase-CLEA for styrene epoxidation. *Chem. Commun.* **2021,** *57*, 5766-5769.
21. Zhu, Z.; Xu, H.; Jiang, J.; Wu, P., Postsynthesis and Effective Baeyer–Villiger Oxidation Properties of Hierarchical FAU-type Stannosilicate. *J. Phys. Chem.* **2016,** *120* (41), 23613-23624.
22. Faraji, A. R.; Ashouri, F.; Hekmatian, Z.; Heydari, S.; Mosazadeh, S., Organosuperbase dendron manganese complex grafted on magnetic nanoparticles; heterogeneous catalyst for green and selective oxidation of ethylbenzene, cyclohexene and oximes by molecular oxygen. *Polyhedron* **2019,** *157*, 90-106.
23. Chao, R. R.; Lau, I. C. K.; Coleman, T.; Churchman, L. R.; Child, S. A.; Lee, J. H.; Bruning, J. B.; De Voss, J. J.; Bell, S. G., The Stereoselective Oxidation of para‐Substituted Benzenes by a Cytochrome P450 Biocatalyst. *Eur. J. Chem.* **2021,** *27* (59), 14765-14777.
24. Farokhi, A.; Berijani, K.; Hosseini-Monfared, H., Manganes-porphyrin as efficient enantioselective catalyst for aerobic epoxidation of olefins. *Catal. Lett.* **2018,** *148* (8), 2608-2618.
25. Toda, H.; Imae, R.; Itoh, N., Bioproduction of Chiral Epoxyalkanes using Styrene Monooxygenase from Rhodococcus sp. ST‐10 (RhSMO). *Adv. Synth. Catal.* **2014,** *356* (16), 3443-3450.

26. Zhang, X.; Yang, H.; Yang, G.; Li, S.; Wang, X.; Ma, J., Metal-Free Mesoporous SiO2 Nanorods as a Highly Efficient Catalyst for the Baeyer–Villiger Oxidation under Mild Conditions. *ACS Sustain. Chem. Eng.* **2018,** *6* (5), 5868-5876.
27. Beneventi, E.; Niero, M.; Motterle, R.; Fraaije, M.; Bergantino, E., Discovery of Baeyer–Villiger monooxygenases from photosynthetic eukaryotes. *J. Mol. Catal. B Enzym.* **2013,** *98*, 145-154.
28. Shiraishi, Y.; Saito, N.; Hirai, T., Adsorption-driven photocatalytic activity of mesoporous titanium dioxide. *J. Am. Chem. Soc.* **2005,** *127* (37), 12820-12822.
29. Lin, X.; Zhou, Z.; Li, Q. Y.; Xu, D.; Xia, S. Y.; Leng, B. L.; Zhai, G. Y.; Zhang, S. N.; Sun, L. H.; Zhao, G., Direct Oxygen Transfer from H2O to Cyclooctene over Electron‐Rich RuO2 Nanocrystals for Epoxidation and Hydrogen Evolution. *Angew. Chem.* **2022,** *134* (35), e202207108.
30. Calvete, M. J.; Piñeiro, M.; Dias, L. D.; Pereira, M. M., Hydrogen peroxide and metalloporphyrins in oxidation catalysis: old dogs with some new tricks. *ChemCatChem* **2018,** *10* (17), 3615-3635.
31. Lee, J. H.; Podgorski, M. N.; Moir, M.; Gee, A. R.; Bell, S. G., Selective oxidations using a cytochrome P450 enzyme variant driven with surrogate oxygen donors and light. *Chem. Eur. J* **2022,** *28* (49), e202201366.
32. Malkov, A. V.; Friscourt, F.; Bell, M.; Swarbrick, M. E.; Kocovský, P., Enantioselective Baeyer–Villiger oxidation catalyzed by Palladium (II) complexes with chiral P, N-Ligands. *J. Org. Chem.* **2008,** *73* (11), 3996-4003.
33. Mazur, M.; Janeczko, T.; Gładkowski, W., Lipase-mediated Baeyer–Villiger oxidation of benzylcyclopentanones in ester solvents and deep eutectic solvents. *Sci. Rep.* **2022,** *12* (1), 14795.