OL | Organic Letters

Letter

Cite This: Org. Lett. XXXX, XXX, XXX−XXX

pubs.acs.org/OrgLett

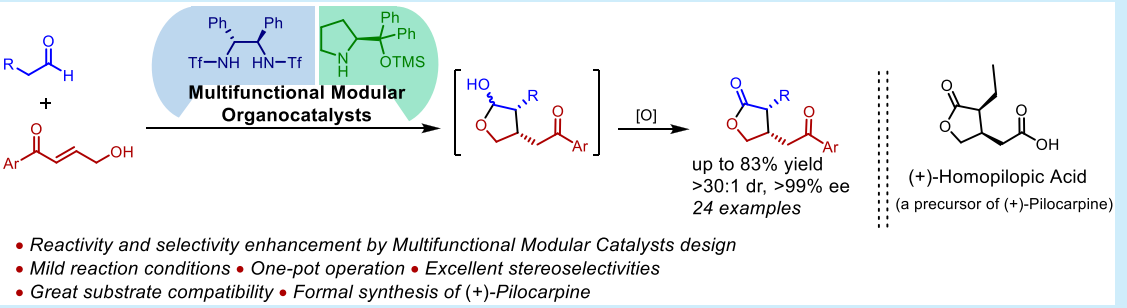
Asymmetric Multifunctional Modular Organocatalysis: One-Pot Direct Strategy to Enantiopure α,β-Disubstituted γ-Butyrolactones

Pratibha Mahto,[†] Nirmal K. Rana,[‡] Khyati Shukla,[†] Braja G. Das,[†] Harshit Joshi,[†] and Vinod K. Singh*[,†]

[†]Department of Chemistry, Indian Institute of Technology Kanpur, Kanpur - 208 016, UP, India

[‡]Department of Chemistry, Indian Institute of Technology Jodhpur, Jodhpur - 342 037, Rajasthan, India

Supporting Information



ABSTRACT: A simple and efficient approach to enantioenriched α,β-disubstituted γ-butyrolactones has been developed through multifunctional modular organocatalysis in a highly enantioselective (>99% ee) and diastereoselective (>30:1) manner following a one-pot sequential Michael−hemiacetalization−oxidation reaction. The catalytic process has great substrate compatibility, and the products have been transformed to synthetically useful molecules. The methodology has also been applied to the formal synthesis of (+)-Pilocarpine.

One-pot sequential reaction is one of the most dynamic and powerful synthetic strategies especially in the field of asymmetric organic synthesis. Endowed with the advantages of sustainability, cost, time effectiveness, step economy, and low waste production, one-pot operation provides efficient pathways for the execution of multiple transformations involving the formation of multiple C−C and/or C−X bonds.[1] Owing to the numerous advantages, asymmetric one-pot reactions have been frequently utilized in manufacturing small to complex chiral molecules including heterocycles.[2]

γ-Butyrolactones, oxygen-rich five-membered heterocycle scaffolds, are found in a diverse range of natural products and pharmaceutically significant molecules.[3] Furthermore, they serve as versatile intermediates in synthesizing complex molecules.[4] A few selected examples are shown in Figure 1. Therefore, the ubiquity of a γ-butyrolactone motif and its significant bioactivities makes it quite imperative to explore and map new methodologies. Thus, in recent years, with the advent of organocatalytic tandem/cascade reactions,[5] a wide variety of stereoselective processes have been established to access optically active butyrolactones.[6] The majority of organocatalytic methods to construct γ-butyrolactones are directed toward the use of NHC catalysis.[7] In 2015, Xu et al. reported an enantioselective route to trisubstituted γ-lactones via addition of aldehydes to activated α,β-unsaturated ketones bearing a carboxylic acid group at β-position which proved to be essential for reactivity as well as selectivity (Scheme 1a).[8]

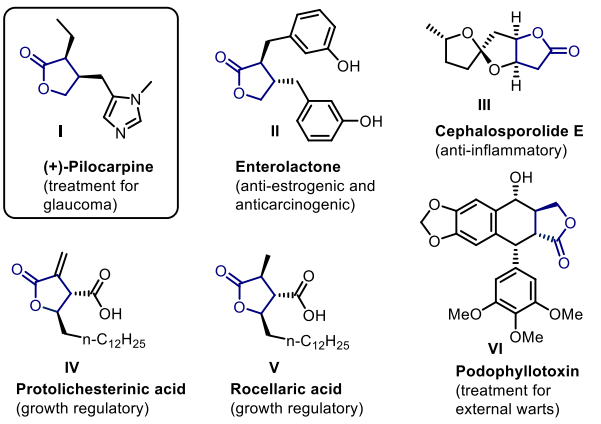


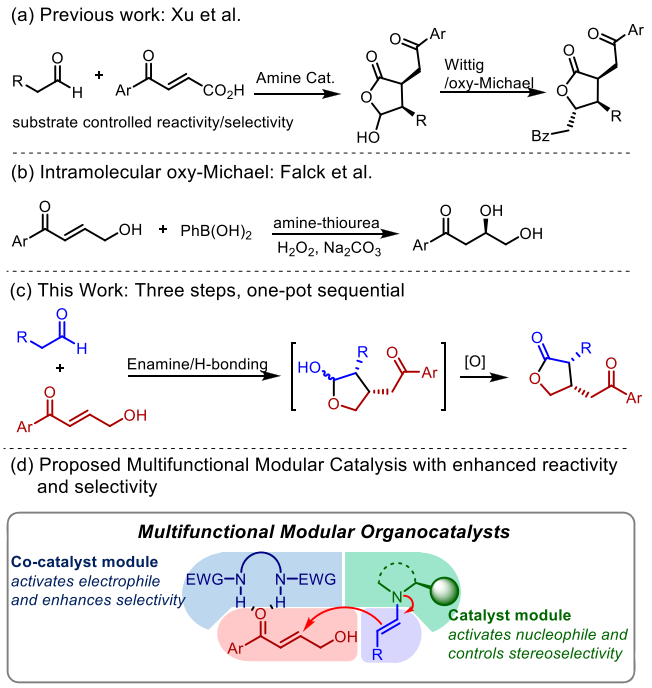
Figure 1. Selected examples of biologically relevant molecules having γ-butyrolactone core.

Other significant developments involving amine catalysis include Michael−cyclization cascades of several active nucleophiles such as indoles,[9] boronic acid,[10] and α-hydroxy ketones.[11] However, direct asymmetric organocatalytic methods to construct chiral α,β-disubstituted γ-butyrolactones remain elusive.[12] Therefore, a straightforward approach

Received: June 18, 2019

DOI: 10.1021/acs.orglett.9b02094
Org. Lett. XXXX, XXX, XXX−XXX

Scheme 1. Background

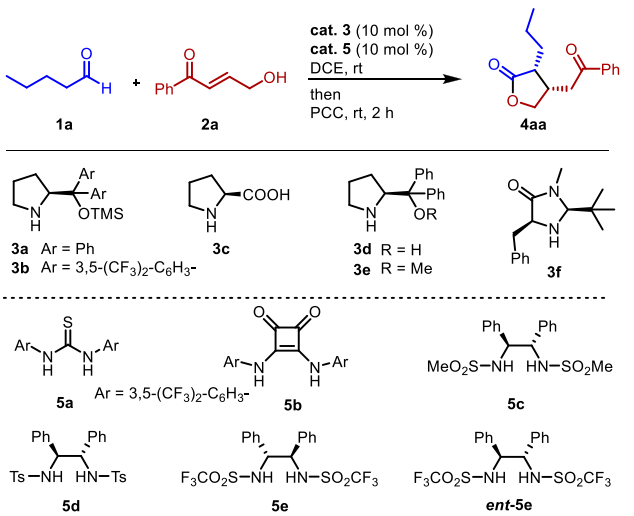


utilizing simple starting materials under mild reaction conditions for creating chiral γ-butyrolactones in a highly enantio- and diastereoselective as well as one-pot fashion is still desired. Following the pioneering work of Falck et al. on intramolecular oxy-Michael reaction (Scheme 1b),[13] several groups have utilized the bidentate substrate γ-hydroxy α,β-unsaturated ketone as a potential synthon in many catalytic asymmetric transformations.[14]

In our continuous effort to develop efficient and novel asymmetric approaches for the synthesis of chiral molecules,[15] we envisioned that the γ-hydroxy α,β-unsaturated ketone could be employed as a Michael acceptor in an enamine catalysis with simple aldehyde to efficiently produce substituted γ-lactol which could in principle be oxidized in situ to γ-butyrolactone (Scheme 1c). However, this would be challenging because of the following: (i) low electrophilicity at the β-carbon of the α,β-unsaturated ketone toward the addition of enamine, (ii) formation of unwanted acetal in the presence of an aldehyde, (iii) dimerization and control of enantiofacial selectivity. Thus, the choice of catalysts is of utmost importance. Cooperative hydrogen bond donor catalytic systems could be suitable here, and these have been proven to be efficient tools for several asymmetric transformations.[16] However, these are mainly limited to anion-binding catalysis in which substrates are capable of forming stabilized, conjugate ionic intermediates.[17] It was hypothesized that a multifunctional modular assembly of two distinct catalysts could successfully be engaged to overcome these challenges. As depicted in Scheme 1d, a secondary amine catalyst would form enamine while the H-bond donor cocatalyst would activate the γ-hydroxy α,β-unsaturated ketone to increase its reactivity as well as selectivity. Since these two catalyst modules are not joined by any covalent bond, each module could individually be tuned easily as desired. Further, this would provide more scope to build a modular catalysts library and reduce both the time and the cost of the screening process. Herein, we report an efficient direct asymmetric one-pot synthesis of α,β-disubstituted γ-butyrolactone via Michael–hemiacetalization–oxidation.

At the outset, model substrates valeraldehyde (**1a**) and (*E*)-4-hydroxy-1-phenyl-2-en-1-one (**2a**) were stirred at room temperature with 10 mol % of Hayashi–Jørgensen catalyst[18] (**3a**) in dichloroethane. Despite some expectations, only a 12% yield of desired γ-butyrolactone **4aa** was isolated after continuing the reaction for 7 days followed by in situ oxidation with pyridinium chlorochromate (PCC). Pleasingly, the enantiomeric excess of the γ-lactone **4aa** was determined to be >99% (Table 1, entry 1). In a traditional way,[19] reaction conditions were varied to increase the yield, but the results were disappointing.[20] Concerned about the yield of the reaction and to check the feasibility of our hypothesis, we

Table 1. Screening of Multifunctional Modular Organocatalysts[a]



entry	cat. 3	cat. 5	time (d)	yield (%)	dr[b]	ee[c] (%)
1	**3a**	–	7	12	20:1	>99
2	**3a**	**5a**	3	29	20:1	98
3	**3a**	**5b**	3	32	20:1	98
4	**3a**	**5c**	3	62	>30:1	>99
5	**3a**	**5d**	3	64	>30:1	99
6	**3a**	**5e**	2	78	>30:1	>99
7	**3b**	**5e**	5	trace	–	–
8	**3d**	**5e**	5	trace	–	–
9	**3e**	**5e**	3	52	>30:1	96
10	**3f**	**5e**	5	trace	–	–
11[d]	**3c**	–	7	12	16:1	17
12[e]	**3a**	**5e**	2	62	>30:1	>99
13	**3a**	***ent*-5e**	2	74	>30:1	>99
14[f]	***ent*-3a**	**5e**	2	72	>30:1	>99
15[f]	***ent*-3a**	***ent*-5e**	2	72	>30:1	>99
16[g]	**3a**	**5e**	4	trace	–	>99
17[h]	**3a**	**5e**	2.5	70	>30:1	>99

[a]Reaction conditions: **1a** (34.4 mg, 0.4 mmol), **2a** (32.4 mg, 0.2 mmol), **3** (0.02 mmol), **5** (0.02 mmol), DCE (1 mL), PCC (129.3 mg, 0.6 mmol), unless noted otherwise. [b]Determined by the ^{1}H NMR analysis of crude reaction mixture. [c]Determined by chiral HPLC analysis. [d]10 mol % DMAP was used in place of cat. **5**. [e]The intermediate lactol was isolated and then oxidized using PCC. [f]The opposite enantiomer was obtained. [g]Conditions for Anelli oxidation were used instead of PCC. [h]The reaction was conducted in 2.5 mmol scale.

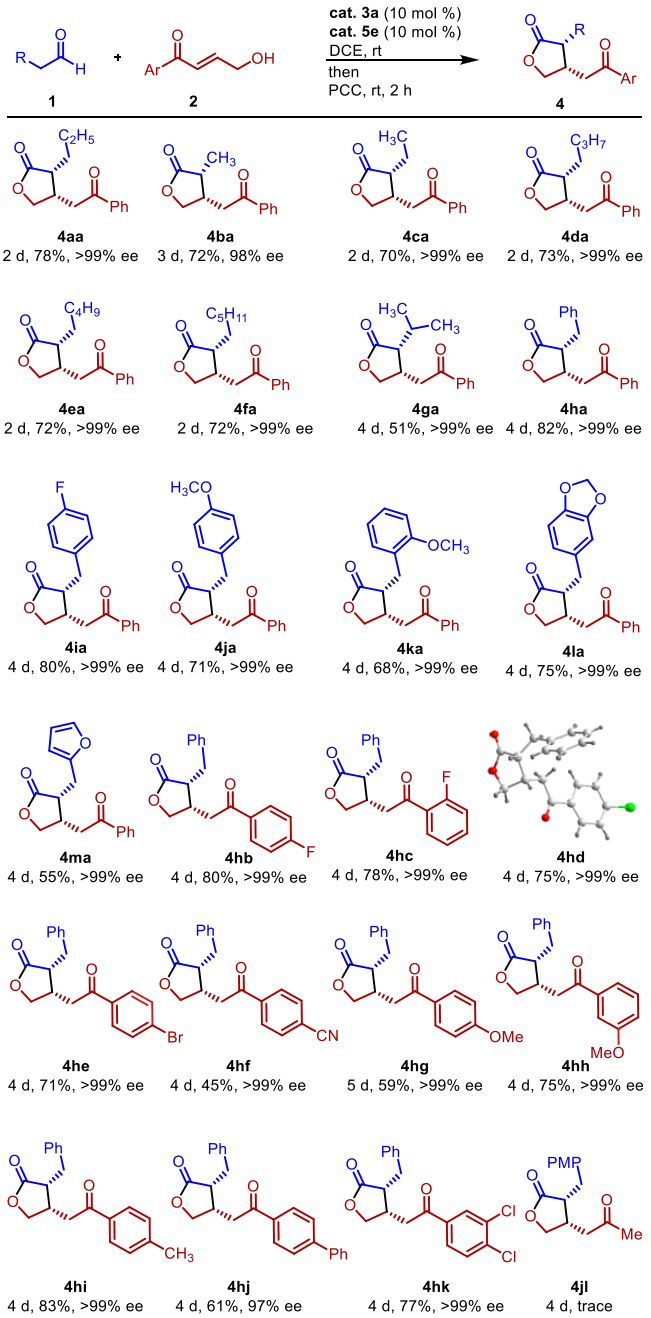
DOI: 10.1021/acs.orglett.9b02094
Org. Lett. XXXX, XXX, XXX–XXX

thought to employ the multifunctional modular catalysts assemblies. Initially, the combination of catalyst **3a** with a series of cocatalyst modules **5a−e** was tested. To our delight, the yield of the reactions improved significantly and the combination of catalyst **3a** and **5e** proved to be the best and delivered γ-butyrolactone **4aa** in 78% yield in just 2 days (Table 1, entry 6). It is worth noting that the use of combined catalysts proved advantageous in improving the diastereomeric ratio of the product. These observations clearly pointed out the significant role of multifunctional modular catalysis in the rate enhancement as well as diastereoselectivity of the reaction.

After resolving the yield crunch, we studied the effect of various secondary amine based catalysts **3b** and **3d−f**. In sharp contrast to the accelerated rate observed with combined catalysts **3a** and **5e**, chiral secondary amines **3b** and **3d** screened in combination with **5e** in the Michael−hemiacetalization reaction resulted in only trace amount of the product. Notably, the combined catalysts **3e** and **5e** gave a good yield (52%) with slightly lower enantioselectivity. However, imidazolidinone catalyst **3f** was found to be inefficient for this reaction. In a control experiment, when the reactions were conducted in a two-pot operation, the isolated yield of **4aa** was slightly lower but stereoselectivities were comparable to the one-pot process (Table 1, entry 12). Encouraged by the profound success of synergistic catalysis, the effect on stereoselectivity by employing different combinations of enantiomeric catalyst partners was investigated. It was observed that the absolute stereochemistry of **5e** (or *ent*-**5e**) had no influence on the outcome of the absolute stereochemistry of the product and the stereoselectivity as well. On the other hand, employing *ent*-**3a** in combination with cocatalyst **5e**, as expected, provided access to the opposite enantiomer of γ-butyrolactone **4aa** in synthetically viable yield with excellent stereoselectivities (>30:1 dr, 99% ee). These observations indicate that there was no matched and mismatched combination of chiral catalyst modules. Although the oxidation step was successfully performed by PCC, a green alternative, e.g., Anelli oxidation has also been tested. Unfortunately, the conversion in the oxidation step was very low (Table 1, entry 16), but the enantioselectivity remained unaltered (>99%). The model reaction was scaled up to 2.5 mmol providing **4aa** in 70% yield and >99% ee (Table 1, entry 17).

After establishing the optimized reaction conditions and the best combination of catalysts, we proceeded to explore the substrate scope of the one-pot sequential Michael−hemiacetalization−oxidation reaction. A series of primary aldehydes were first investigated with (*E*)-4-hydroxy-1-phenyl-2-en-1-one (**2a**) (Scheme 2). In general, short- (R = Me) to long-chain (R = *n*-hex) aldehydes smoothly underwent the one-pot sequential reaction to afford the desired α,β-disubstituted γ-butyrolactones **4aa−fa** in high yields with excellent stereoselectivities (up to >30:1 dr, >99% ee). Importantly, sterically demanding isovaleraldehyde (**1g**) was also compatible with the catalytic process. Albiet with a prolonged reaction time, corresponding product **4ga** was isolated in 51% yield and >99% ee. Dihydrocinnamaldehydes **1h−k** bearing different substituents (4-F-, 4-MeO-, 2-MeO-) on the aromatic ring successfully reacted with **2a**, affording diverse γ-butyrolactones **4ha−ka** in almost enantiomerically pure form. Interestingly, an optically pure γ-butyrolactone **4la** featuring a piperonyl group at the α-carbon could also be synthesized using our current protocol. Additionally, 3-(furan-2-yl)propanal was well tolerated, offering the corresponding product **4ma** in moderate yield with excellent enantioselectivity.

Scheme 2. Scope of One-Pot Sequential Michael−Hemiacetalization−Oxidation Reaction[a,b]



[a]Reaction conditions: **1a** (0.4 mmol), **2a** (0.2 mmol), **3** (0.02 mmol), **5** (0.02 mmol), DCE (1 mL), PCC (129.3 mg, 0.6 mmol), unless noted otherwise. [b]Dr was determined to be >30:1 for all cases by ^{1}H NMR of the crude reaction mixture, unless specified.

The one-pot sequential Michael−hemiacetalization−oxidation strategy was further explored by incorporating a number of different substituents on the aryl ring of Michael acceptors **2**. As presented in Scheme 2, γ-hydroxy-α,β-unsaturated ketones having halogens (fluoro, chloro, bromo) at *para*- and *ortho*-positions of the aryl ring were successfully employed with dihydrocinnamaldehyde (**1h**), producing the disubstituted γ-lactones **4hb−he** in high yields with excellent stereo-

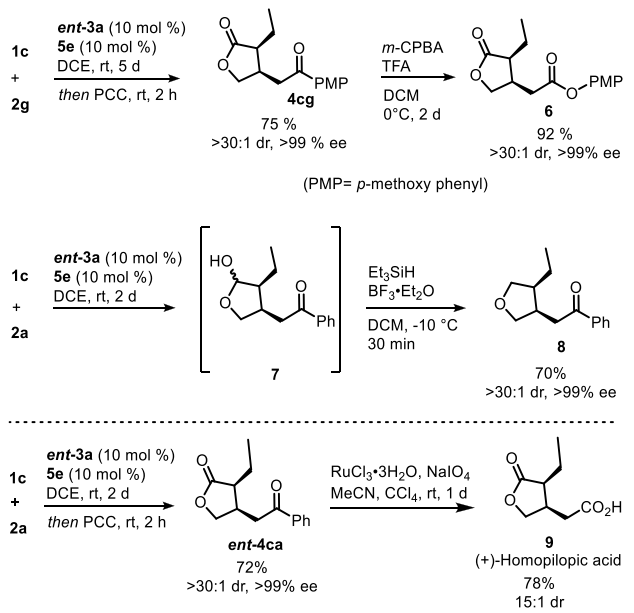
DOI: 10.1021/acs.orglett.9b02094
Org. Lett. XXXX, XXX, XXX−XXX

selectivities. In addition, an electron-withdrawing (nitrile) and moderate to strong electron-releasing groups (methyl, methoxy) on the aromatic ring of the Michael acceptor were also compatible under current catalytic system. Moreover, γ-butyrolactones containing biphenyl **4hj** and 3,4-dichlorophenyl **4hk** ketone units were achieved in synthetically viable yields and excellent enantioselectivities. To understand the versatility of the methodology toward alkyl enone, (*E*)-5-hydroxypent-3-en-2-one (**2l**) was allowed to react with *p*-methoxy hydrocinnamaldehyde (**1j**) under optimized reaction conditions. However, only a trace amount of lactone product **4jl** was detected. Thus, it may be concluded that the present method is only suitable for aryl ketones.

The absolute stereochemistry of compound **4hd** (R = $-CH_2C_6H_5$; Ar = 4-Cl-C_6H_4−) (CCDC: 1923223) was unambiguously determined by the single-crystal X-ray analysis.[20] The stereochemistry of related γ-butyrolactone products were assigned by analogy.

To illustrate the synthetic utility of our catalytic method, the γ-butyrolactone or γ-lactol was further subjected to several organic transformations (Scheme 3). Initially, the γ-lactone

Scheme 3. Synthetic Transformations and Formal Synthesis of (+)-Pilocarpine



4cg bearing a *para*-methoxy group was transformed to the corresponding ester **6** without erosion of any enantiopurity via Baeyer−Villiger oxidation. The intermediate hemiacetal **7** formed by the reaction of butyraldehyde (**1c**) with **2a** using the combination of catalysts *ent*-**3a** and **5e** under optimal reaction conditions was successfully transformed to disubstituted tetrahydrofuran **8** with high enantioselectivity of >99% and 70% yield. It is interesting to note that the ketone moiety remained intact during this transformation. Finally, the present one-pot protocol was applied to the formal asymmetric synthesis of (+)-Pilocarpine. (+)-Pilocarpine (**I**) is found in the pilocarpus *Jaborandi* species and is frequently prescribed for the treatment of narrow and wide angle glaucoma. The hemiacetal **7** on in situ oxidation gave the corresponding γ-butyrolactone **4ca** which was then successfully converted in one step to (+)-Homopilopic acid **9**, a synthetic precursor[21] of (+)-Pilocarpine.

In summary, a one-pot sequential Michael−hemiacetalization−oxidation strategy has been developed using multifunctional modular organocatalysts, enabling a simple yet highly diastereo- and enantioselective synthesis of γ-butyrolactones possessing two contiguous stereogenic centers. The present catalytic method is compatible with a diverse range of substrates. The synthetic utility of this methodology was demonstrated by functional group elaboration and its implementation in the formal asymmetric synthesis of (+)-Pilocarpine. Further studies toward the understanding of reactivity and selectivity enhancement by multifunctional modular catalysis and the development of newer approaches for synthesizing complex molecular architectures are currently underway in our laboratory.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.9b02094.

Experimental procedures and analytical data (PDF)

Accession Codes

CCDC 1923223 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: vinodks@iitk.ac.in.

ORCID

Vinod K. Singh: 0000-0003-0928-5543

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

V.K.S. acknowledges DST/SERB, India for a J. C. Bose fellowship (SR/S2/JCB-17/2008) and SERB (CRG/2018/000552) for a research grant. P.M., K.S., and H.J. thank IIT Kanpur, CSIR and UGC, India, respectively, for a doctoral fellowship. N.K.R. and B.G.D. thank DST, India for an INSPIRE Faculty award. We thank Vierandra Kumar, IIT Kanpur, for assistance with X-ray crystallography and IIT Kanpur for instrumentation facilities.

■ REFERENCES

(1) For recent reviews, see: (a) Hong, B.-C.; Raja, A.; Sheth, V. M. *Synthesis* **2015**, *47*, 3257−3285. (b) Hayashi, Y. *Chem. Sci.* **2016**, *7*, 866−880. (c) Corma, A.; Navas, J.; Sabater, M. J. *Chem. Rev.* **2018**, *118*, 1410−1419.

(2) Yanai, H. *Chapter 10 - Green and Catalytic Methods for γ-Lactone Synthesis. Green Synthetic Approaches for Biologically Relevant Heterocycles*; Brahmachari, G., Ed.; Elsevier: Boston, 2015; pp 257−289.

(3) (a) Janecki, T. *Natural Lactones and Lactams: Synthesis Occurrence and Biological Activity*; Wiley-VCH: Germany, 2013. (b) Watson, P. G. *Br. J. Ophthalmol.* **1972**, *56*, 145. (c) Horne, D. A.; Fugmann, B.; Yakushijin, K.; Buchi, G. *J. Org. Chem.* **1993**, *58*,

DOI: 10.1021/acs.orglett.9b02094
Org. Lett. XXXX, XXX, XXX−XXX

62−64. (d) Heinonen, S.; Nurmi, T.; Liukkonen, K.; Poutanen, K.; Wähälä, K.; Deyama, T.; Nishibe, S.; Adlercreutz, H. *J. Agric. Food Chem.* **2001**, *49*, 3178−3186. (e) Oller-Lopez, J. L.; Iranzo, M.; Mormeneo, S.; Oliver, E.; Cuerva, J. M.; Oltra, J. E. *Org. Biomol. Chem.* **2005**, *3*, 1172−1173. (f) Nallasivam, J. L.; Fernandes, R. A. *Org. Biomol. Chem.* **2017**, *15*, 708−716. (g) Yu, X.; Che, Z.; Xu, H. *Chem. - Eur. J.* **2017**, *23*, 4467−4526.

(4) For a review, see: (a) Kitson, R. R. A.; Millemaggi, A.; Taylor, R. J. K. *Angew. Chem., Int. Ed.* **2009**, *48*, 9426−9451. For recent examples: (b) Rodriguez-Lopez, J.; Ortega, N.; Martin, V. S.; Martin, T. *Chem. Commun.* **2014**, *50*, 3685−3688. (c) Sarkale, A. M.; Kumar, A.; Appayee, C. *J. Org. Chem.* **2018**, *83*, 4167−4172.

(5) (a) Chanda, T.; Zhao, J. C.-G. *Adv. Synth. Catal.* **2018**, *360*, 2−79. (b) Rana, N. K.; Joshi, H.; Jha, R. K.; Singh, V. K. *Chem. - Eur. J.* **2017**, *23*, 2040−2043. (c) Rana, N. K.; Jha, R. K.; Joshi, H.; Singh, V. K. *Tetrahedron Lett.* **2017**, *58*, 2135−2139.

(6) (a) Gil, S.; Parra, M.; Rodriguez, P.; Segura, J. *Mini-Rev. Org. Chem.* **2009**, *6*, 345−358. (b) Kammerer, C.; Prestat, G.; Madec, D.; Poli, G. *Acc. Chem. Res.* **2014**, *47*, 3439−3447. (c) Mao, B.; Fañanás-Mastral, M.; Feringa, B. L. *Chem. Rev.* **2017**, *117*, 10502−10566. For selected examples, see: (d) Wang, L.; Shi, X.-M.; Dong, W.-P.; Zhu, L.-P.; Wang, R. *Chem. Commun.* **2013**, *49*, 3458−3460. (e) Companyó, X.; Mazzanti, A.; Moyano, A.; Janecka, A.; Rios, R. *Chem. Commun.* **2013**, *49*, 1184−1186. (f) Wilent, J. E.; Qabaja, G.; Petersen, K. S. *Org. Synth.* **2017**, *93*, 75−87. (g) Henrion, S.; Mace, A.; Vallejos, M. M.; Roisnel, T.; Carboni, B.; Villalgordo, J. M.; Carreaux, F. *Org. Biomol. Chem.* **2018**, *16*, 1672−1678. (h) Claveau, R.; Twamley, B.; Connon, S. J. *Chem. Commun.* **2018**, *54*, 3231−3234. (i) Jiang, X.; Liu, S.; Yang, S.; Jing, M.; Xu, L.; Yu, P.; Wang, Y.; Yeung, Y.-Y. *Org. Lett.* **2018**, *20*, 3259−3262.

(7) For reviews on NHC catalysis, see: (a) Flanigan, D. M.; Romanov-Michailidis, F.; White, N. A.; Rovis, T. *Chem. Rev.* **2015**, *115*, 9307−9387. (b) Murauski, K. J. R.; Jaworski, A. A.; Scheidt, K. A. *Chem. Soc. Rev.* **2018**, *47*, 1773−1782 For selected examples, see: . (c) Li, Y.; Zhao, Z.-A.; He, H.; You, S.-L. *Adv. Synth. Catal.* **2008**, *350*, 1885−1890. (d) Kaeobamrung, J.; Bode, J. W. *Org. Lett.* **2009**, *11*, 677−680. (e) Cardinal-David, B.; Raup, D. E. A.; Scheidt, K. A. *J. Am. Chem. Soc.* **2010**, *132*, 5345−5347. (f) Sun, L.-H.; Shen, L.-T.; Ye, S. *Chem. Commun.* **2011**, *47*, 10136−10138. (g) Dugal-Tessier, J.; O'Bryan, E. A.; Schroeder, T. B. H.; Cohen, D. T.; Scheidt, K. A. *Angew. Chem., Int. Ed.* **2012**, *51*, 4963−4967. (h) Mukherjee, S.; Joseph, S.; Bhunia, A.; Gonnade, R. G.; Yetra, S. R.; Biju, A. T. *Org. Biomol. Chem.* **2017**, *15*, 2013−2019.

(8) Lin, J.-B.; Xu, S.-M.; Xie, J.-K.; Li, H.-Y.; Xu, P.-F. *Chem. Commun.* **2015**, *51*, 3596−3599.

(9) Riguet, E. *J. Org. Chem.* **2011**, *76*, 8143−8150.

(10) Bos, M.; Riguet, E. *J. Org. Chem.* **2014**, *79*, 10881−10889.

(11) (a) He, G.; Wu, F.; Huang, W.; Zhou, R.; Ouyang, L.; Han, B. *Adv. Synth. Catal.* **2014**, *356*, 2311−2319. (b) Balha, M.; Mondal, B.; Sahoo, S. C.; Pan, S. C. *J. Org. Chem.* **2017**, *82*, 6409−6416. (c) Khopade, T. M.; Sonawane, A. D.; Arora, J. S.; Bhat, R. G. *Adv. Synth. Catal.* **2017**, *359*, 3905−3910.

(12) Peraino, N. J.; Kaster, S. H.; Wheeler, K. A.; Kerrigan, N. J. *J. Org. Chem.* **2017**, *82*, 606−615.

(13) Li, D. R.; Murugan, A.; Falck, J. R. *J. Am. Chem. Soc.* **2008**, *130*, 46−48.

(14) (a) Inokuma, T.; Takasu, K.; Sakaeda, T.; Takemoto, Y. *Org. Lett.* **2009**, *11*, 2425−2428. (b) Asano, K.; Matsubara, S. *Org. Lett.* **2012**, *14*, 1620−1623. (c) Fukata, Y.; Asano, K.; Matsubara, S. *Chem. Lett.* **2013**, *42*, 355−357. (d) Fukata, Y.; Asano, K.; Matsubara, S. *J. Am. Chem. Soc.* **2013**, *135*, 12160−12163. (e) Yoneda, N.; Hotta, A.; Asano, K.; Matsubara, S. *Org. Lett.* **2014**, *16*, 6264−6266. (f) Huang, S.-H.; Shih, Y.-W.; Huang, W.-T.; Li, D.-H.; Yang, T.-F. *RSC Adv.* **2016**, *6*, 91870−91874. (g) Mondal, B.; Mondal, K.; Satpati, P.; Pan, S. C. *Eur. J. Org. Chem.* **2017**, *2017*, 7101−7106. (h) Mondal, B.; Balha, M.; Pan, S. C. *Asian J. Org. Chem.* **2018**, *7*, 1788−1792. (i) Mondal, K.; Pan, S. C. *J. Org. Chem.* **2018**, *83*, 5301−5312. (j) Matsumoto, A.; Asano, K.; Matsubara, S. *Org. Lett.* **2019**, *21*, 2688−2692.

(15) (a) Kamble, R. M.; Singh, V. K. *Tetrahedron Lett.* **2003**, *44*, 5347−5349. (b) Bisai, V.; Suneja, A.; Singh, V. K. *Angew. Chem., Int. Ed.* **2014**, *53*, 10737−10741.

(16) (a) Wang, M. H.; Cohen, D. T.; Schwamb, C. B.; Mishra, R. K.; Scheidt, K. A. *J. Am. Chem. Soc.* **2015**, *137*, 5891−5894. (b) Maskeri, M. A.; O'Connor, M. J.; Jaworski, A. A.; Davies, A. V.; Scheidt, K. A. *Angew. Chem., Int. Ed.* **2018**, *57*, 17225−17229.

(17) For reviews, see: (a) Zhang, Z.; Schreiner, P. R. *Chem. Soc. Rev.* **2009**, *38*, 1187−1198. (b) Brière, J.-F.; Oudeyer, S.; Dalla, V.; Levacher, V. *Chem. Soc. Rev.* **2012**, *41*, 1696−1707. (c) Inamdar, S. M.; Shinde, V. S.; Patil, N. T. *Org. Biomol. Chem.* **2015**, *13*, 8116−8162. (d) Anebouselvy, K.; Shruthi, K. S.; Ramachary, D. B. *Eur. J. Org. Chem.* **2017**, *2017*, 5460−5483 For selected examples, see: . (e) Burns, N. Z.; Witten, M. R.; Jacobsen, E. N. *J. Am. Chem. Soc.* **2011**, *133*, 14578−14581. (f) Gu, Y.; Wang, Y.; Yu, T.-Y.; Liang, Y.-M.; Xu, P.-F. *Angew. Chem., Int. Ed.* **2014**, *53*, 14128−14131. (g) Wang, Y.; Yu, T.-Y.; Zhang, H.-B.; Luo, Y.-C.; Xu, P.-F. *Angew. Chem., Int. Ed.* **2012**, *51*, 12339−12342. (h) Xu, H.; Zuend, S. J.; Woll, M. G.; Tao, Y.; Jacobsen, E. N. *Science* **2010**, *327*, 986−990.

(18) Jensen, K. L.; Dickmeiss, G.; Jiang, H.; Albrecht, L.; Jørgensen, K. L. *Acc. Chem. Res.* **2012**, *45*, 248−264.

(19) Hong, L.; Sun, W.; Yang, D.; Li, G.; Wang, R. *Chem. Rev.* **2016**, *116*, 4006−4123.

(20) For details, see Supporting Information.

(21) (a) Csuk, R.; Woeste, B. *Tetrahedron* **2008**, *64*, 9384−9387. (b) Davies, S. G.; Roberts, P. M.; Stephenson, P. T.; Storr, H. R.; Thomson, J. E. *Tetrahedron* **2009**, *65*, 8283−8296.

DOI: 10.1021/acs.orglett.9b02094
Org. Lett. XXXX, XXX, XXX−XXX