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Tandem reaction of 1,2-allenic ketone with α -halo ketone or α -halo ester in water: an efficient and sustainable synthesis of 1,3,4'-tricarbonyl compounds[†]

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An efficient and sustainable synthesis of the otherwise difficult to obtain 1,3,4'-tricarbonyl compounds through a water mediated, TBAF·3H₂O promoted unprecedented tandem reaction of 1,2-allenic ketone with α -halo ketone or α -halo ester has been developed. Remarkably enhanced reactivity and improved chemoselectivity by using water as the reaction medium was observed. The 1,3,4'-tricarbonyl compounds facilitate further versatile transformations, which underscores the importance of these products as synthetic intermediates.

Introduction

Activated allenes with electron-withdrawing groups, such as sulfonyl, phosphoryl, or alkoxycarbonyl have significantly higher electrophilicities compared to the corresponding allenes. The proton attached to the α - or γ -carbon of the activated allenes is acidic enough to be abstracted by different bases and the allenyl anion species thus generated can be used as nucleophiles for a variety of carbon–carbon bond formations. Recently, elegant protocols for the synthesis of a variety of interesting compounds have been developed by the Hammond group by using an allenyl ester as an activated allene substrate (Scheme 1).¹⁻³



Scheme 1 Nucleophilic reactions of anions derived from an allenyl ester.

On the other hand, 1,4-diketones are important synthetic precursors to carbocyclic⁴ or heterocyclic compounds.⁵ Due to their importance, various synthetic procedures toward 1,4-diketones have been developed.⁶⁻⁸ While these methods are generally efficient and reliable, some of them suffer from delicate reaction conditions, tedious procedures, or the generation of hazardous wastes. Therefore, it is desirable to develop a more practical and sustainable synthetic pathway toward 1,4-diketones.

As versatile and valuable synthetic intermediates,⁹⁻¹² allenic ketones can be considered as keto activated allenes. Based on the chemistry exhibited by allenyl ester as shown in Scheme 1, we envisioned a new approach toward functionalized 1,4-diketones through the reaction of allenic ketone (1) with α -haloketone (2) *via* an α -allenic anion intermediate, as shown in Scheme 2. To our surprise, subsequent investigation on its feasibility showed that instead of the desired 1,4-diketone, an unexpected 1,3,4'-triketone was obtained from the reaction of 1 and 2. Herein we would like to report our preliminary results in this regard.



Scheme 2 The proposed formation of 1,4-diketone from 1,2-allenic ketone.

Results and discussion

Initially, 1-phenylbuta-2,3-dien-1-one (1a) and bromoacetophenone (2a) were treated with TBAF \cdot 3H₂O in THF.³ The reaction

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Table 1Optimization of the reaction conditions for the preparation of $3a^a$

	Ph +	Ph Br —	solvent Ph	Ph CH ₃ + Ph		Ph + F	Ph	
	1a	2a	3a	Ph	4a	5a	6a	
Entry	Base (equiv)	Solvent	Temp.(°C)	Time (h)	3a (%) ^b	4a (%) ^b	5a (%) ^b	6a (%) ^b
1	$TBAF \cdot 3H_2O(1)$	THF	60	4	38	8	10	8
2	$TBAF \cdot 3H_2O(2)$	THF	60	4	50	8	12	trace
3	$TBAF \cdot 3H_2O(2)$	DMF	60	4	45	trace	15	10
4	$TBAF \cdot 3H_2O(2)$	CH ₃ CN	60	4	40	trace	18	9
5	$TBAF \cdot 3H_2O(2)$	CH ₃ OH	reflux	4	43	15	trace	10
6	$TBAF \cdot 3H_2O(2)$	C ₂ H ₅ OH	60	4	25	18	trace	10
7	$TBAF \cdot 3H_2O(2)$	CH_2Cl_2	reflux	4	22	trace	10	trace
8	$TBAF \cdot 3H_2O(2)$	Et_2O	reflux	4	21	trace	10	trace
9	$TBAF \cdot 3H_2O(2)$	H_2O	60	3	72	trace	8	trace
10	$Na_2CO_3(2)$	H_2O	60	5	30	12	_	25
11	$K_2 CO_3 (2)$	H_2O	60	5	30	15	_	28
12	NaOH (2)	H_2O	60	5	27	15	_	35
13	$Et_3N(2)$	H_2O	60	5	10	15	_	
14	_	H_2O	60	2	_	_	_	
15	$TBAF \cdot 3H_2O(2)$	H_2O	70	2	74	trace	trace	trace
16	TBAF $3H_2O(2)$	H ₂ O	80	2	79	trace	trace	trace
17	$TBAF \cdot 3H_2O(2)$	H_2O	90	2	77	trace	trace	trace
18	$TBAF \cdot 3H_2O(2)$	H_2O	100	2	70	trace	trace	trace

was allowed to proceed at 60 °C for 4 h. Separation of the resulting mixture gave four products and NMR spectra showed that none of them was the expected 2-allenyl or 2-alkynyl 1,4-dicarbonyl compound, as shown in Scheme 2. Through NMR, MS and X-ray diffraction analysis (Fig. 1), the major product was identified as 2-acetyl-1,4-diphenylbutane-1,4-dione, a 1,3,4'-triketone (**3a**, 38%, Table 1, entry 1). Structures of the three minor products were also established as 1-phenylbutane-1,3-dione (**4a**), fluoroacetophenone (**5a**) and hydroxyl acetophenone (**6a**) with yields of 8%, 10% and 8%, respectively.



Fig. 1 The X-ray crystal structure of 1,3,4'-triketone (3a).

The unexpected formation of **3a** turns out to be very interesting. This is not only because it offers new chemistry of allenic ketone as an activated allene, but also due to the fact that 1,3-diketones are also versatile synthetic intermediates toward various organic compounds.¹³ In addition, 1,3-diketones are frequent structural scaffolds of many therapeutic agents.¹⁴ With both 1,4-dicarbonyl and 1,3-dicarbonyl moieties in a single molecule, 1,3,4'-tricarbonyl compounds like **3a** are expected to act as exceptionally valuable synthetic intermediates. On the other hand, a literature survey revealed that even though there were some reports on the synthesis of 1,3,4'-tricarbonyl

compounds, they were obtained either as minor products,^{15*a*} or through a delicate process under the catalysis of cyanide ions,^{15*b*} or *via* alkylation of a 1,3-dicarbonyl compound with an α -halo ketone/ester in volatile solvent with moderate yields.^{15*c*} This urged us to optimize the above process to develop it into an efficient and general protocol for the preparation of 1,3,4'-tricarbonyl compounds.

Thus, the reaction between **1a** and **2a** mediated by different solvents under the promotion of various bases was investigated and the results were listed in Table 1. As mentioned above, treatment of **1a** and **2a** with 1 equiv. of TBAF·3H₂O at 60 °C in THF afforded 2-acetyl-1,4-diphenylbutane-1,4-dione (**3a**) in a yield of 38% (Table 1, entry 1). Upon duplication of TBAF·3H₂O dosage, the yield was improved to 50% (entry 2). To get a more satisfying yield, the reaction was then tried in various solvents, such as DMF, CH₃CN, CH₂Cl₂, Et₂O, CH₃OH or C₂H₅OH. It turned out that none of these routinely used organic solvents gave a higher yield of **3a** increased to 72% (entry 9).

In following studies, several bases were tested by using water as the reaction medium. It was observed that with Na_2CO_3 , K_2CO_3 or NaOH, the reaction gave **3a** in lower yield than that with TBAF·3H₂O (Table 1, entries 10–12). When Et₃N was tried, the reaction was very sluggish and low yielding (entry 13).

The effect of different temperatures on this reaction was then studied. It followed that the reaction gave 3a in a maximum yield of 79% when it was run at 80 °C for 2 h with 2 equiv. of TBAF·3H₂O in water (Table 1, entry 16). Under these conditions, by-products 4a, 5a and 6a were formed only in trace amounts, as indicated by TLC analysis. This result is very encouraging and promising due to the following two reasons: 1) it provides another example in which an organic reaction can

Table 2Scope of the tandem reaction leading to 3^a

		R ¹	$R^2 + R^3 Br$	TBAF•3H ₂ O H ₂ O	$R^1 \xrightarrow{O} R^3$ R^2	
Entry	\mathbf{R}^1	R ²	R ³	<i>t</i> (h)	Product	Yield (%) ^b
1	Ph	Н	Ph	2	H ₃ C 0 3a	79
2	4-CH ₃ -Ph	Н	Ph	2	H ₃ C H ₃ C 3b	80
3	3-CH ₃ -Ph	Н	Ph	1.5	H_{3C}	82
4	4-CH ₃ O-Ph	Н	Ph	2	H ₃ CO H ₃ C O 3d	75
5	3,4-di-CH ₃ O-Ph	Н	Ph	1	$H_{3}CO + H_{3}CO + H_{3$	83
6	Ph	Н	4-Cl-Ph	1.5	$\bigcup_{H_3 \subset O} O O O O O O O O O O O O O O O O O $	77
7	4-CH ₃ -Ph	Н	4-Cl-Ph	1.5	H ₃ C H ₃ C O 3g	80
8	4-CH ₃ O-Ph	Н	4-Cl-Ph	1	$H_{3}CO H_{3}C O H_$	85
9	Ph	Н	4-CH ₃ -Ph	1.5	CH3 H3C 0 0 3i	68
10	4-CH ₃ -Ph	Н	4-CH ₃ -Ph	1	H ₃ C	79
11	4-CH ₃ O-Ph	Н	4-CH ₃ -Ph	1.5	H ₃ CO H ₃ C 3k	82
12	4-CH ₃ -Ph	Н	4-F-Ph	1.5	$H_{3}C \xrightarrow{O} H_{3}C \xrightarrow{O} 31$	81
13	4-CH ₃ O-Ph	Н	4-F-Ph	1	H ₃ CO H ₃ C O 3m	83

Table 2(Contd.)

			$R^2 + R^3 B$	r <mark>TBAF•3H₂O</mark> H₂O	$R^1 \xrightarrow{O} R^3$ R^2	
Entry	\mathbf{R}^1	R ²	R ³	<i>t</i> (h)	Product	Yield (%) ^b
14	4-Cl-Ph	Н	4-F-Ph	1	CI H ₃ C 0 3n	73
15	4-Cl-Ph	Н	3-Cl-Ph	1		73
16	PhCH ₂	Н	Ph	4	H ₃ C O O O O O 3p	43
17	PhCH ₂	Н	4-F-Ph	4	H ₃ C _C O _O C _C C _F 3q	42
18	PhCH ₂ CH ₂	Н	Ph	4	H ₃ C 0 3r	40
19	PhCH ₂ CH ₂	Н	4-F-Ph	4		41
20	CH ₃	Ph	Ph	4	H ₃ C C O O O O O O O O O O O O O O O O O O	45
21	CH ₃	Ph	4-F-Ph	4	H ₃ C _F O _O F ₃ q	51
22	Ph	Н	OCH ₃	2		69
23	4-CH ₃ -Ph	Н	OCH ₃	2	H ₃ C OCH ₃ H ₃ C O 3u	72
24	3-CH ₃ -Ph	Н	OCH ₃	1	H ₃ C OCH ₃ H ₃ C O A	71
25	4-CH ₃ O-Ph	Н	OCH ₃	2	H ₃ CO H ₃ C O H ₃ C O H ₃ C O H ₃ C	75
26	4-Cl-Ph	Н	OCH ₃	2		68



^a Reaction conditions: 1 mmol of 1 and 2, 2 mmol of TBAF·3H₂O, 4 mL of H₂O, 80 °C; ^b Isolated yields.

not only be smoothly carried out but also significantly enhanced and improved by using water as a medium;¹⁶ 2) the development of efficient synthetic procedures mediated by water is of great importance for the sake of green and sustainable chemistry since water is abundant, inexpensive and safe.^{17–19}

With the optimized reaction conditions in hand, the scope of this tandem reaction leading to 1,3,4'-tricarbonyl compounds was investigated by examining various 1.2-allenic ketones and α -halo carbonyl compounds. The results listed in Table 2 revealed that 1-aryl substituted 1,2-allenic ketones with various substituents on the aryl ring underwent this reaction smoothly and afforded 1,3,4'-triketones in good yields (Table 2, entries 1-15). The reaction was also suitable for 1-aliphatic substituted allenic ketones though the yields were much lower (entries 16-19). As a further aspect, 1,4-disubstituted allenic ketones were studied and they could give the corresponding products in moderate yields (entries 20–21). In addition to α -halo ketones, α -halo esters could also act as the electrophile and underwent this tandem process smoothly to give 1,3,4'-keto esters with good efficiency (entries 22-26). It was also noticed that with 1,4diaryl-buta-2,3-dien-1-ones, 2-allenyl-1,4-diketones (7a and 7b), rather than their 1,3,4'-tricarbonyl counterparts, were obtained in moderate yields (Table 1, entries 27-28).

Based on the above observations, the formation of 1,3,4'triketone 3 can be explained on the basis of the tandem process as outlined in Scheme 3. Initial deprotonation of 1 under the promotion of TBAF·3H₂O occurs to afford α -anion A. α -



Scheme 3 A plausible pathway for the formation of a 1,3,4'-tricarbonyl compound from a 1,2-allenic ketone.

Anion **A** would then react with α -bromoketone **2** to give 2allenyl substituted 1,4-dione (**B**). The allenyl moiety of **B** is then hydrolyzed under the promotion of TBAF·3H₂O to yield **3**. With 1,4-diaryl-buta-2,3-dien-1-one as the substrate, the tandem process actually stops at **B**, most likely due to its extra stability toward TBAF·3H₂O promoted hydrolyzation.

The usefulness of the 1,3,4'-tricarbonyl compound (3) as versatile synthetic intermediate was clearly demonstrated by its efficient transformation into various heterocyclic compounds, as shown in Scheme 4. Hence, 3,4,5-trisubstituted pyrazole (8) and 3,4,5-trisubstituted isoxazole (9) were easily accessible by using 3 as a 1,3-dicarbonyl synthetic building synthon. On the other hand, 2,3,5-trisubstituted furan (10) and 2,3,5-trisubstituted thiophene (11) could be smoothly prepared by using 3 as a 1,4-dicarbonyl starting material. Interestingly, by treating 3 with TBAF·3H₂O (4 equiv) at 90 °C in H₂O for 12 h, the acetyl moiety could be removed to yield 1,4-dicarbonyl compound 12, from which, 2,5-disubstituted furan (13) and 2,5-disubstituted pyrrole (14) were synthesized with high efficiency.



Scheme 4 Reagents and conditions: (a) TsOH, toluene, 100 °C; (b) P_2S_5 , toluene, 110 °C; (c) $NH_2NH_2 \cdot H_2O$, HCl (2%), ethanol, 80 °C; (d) $NH_2OH \cdot HCl$, H_2O /ethanol (1:1), 80 °C; (e) TBAF·3H₂O (4 equiv), H_2O , 90 °C, 12 h; (f) TsOH, toluene, 100 °C; (g) NH_4OH (25%), methanol, sealed tube, 50 °C.

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Finally, by using **1a** and **2a** as model substrates, the recovery and reuse of TBAF/H₂O was investigated. Upon completion of the reaction, the resulting mixture was extracted with diethyl ether. To the remaining aqueous phase containing TBAF were added **1a** and **2a**. The mixture was then submitted to similar procedures. The reuse study was repeated for 3 times, from which **3a** was obtained in a yield of 75%, 70% or 56%, respectively.

Experimental

Flash chromatographic purification of products was performed on silica gel (200–300 mesh). Thin-layer chromatography was visualized with UV light (254 and 365 nm). ¹H and ¹³C NMR spectra were determined on a Bruker AC 400 spectrometer as CDCl₃ solutions. Chemical shifts were expressed in parts per million (δ) downfield from the internal standard tetramethylsilane and were reported as s (singlet), d (doublet), t (triplet), m (multiplet) and coupling constants *J* were given in Hz. Mass spectra were obtained in API mode using a Waters Acquity SQ HPLC-mass spectrometer. The HRMS (High-Resolution Mass Spectra) were performed on a JEOL HX 110A spectrometer.

A typical procedure for the synthesis of 3a through tandem reaction in water

To a flask containing 1-phenylbuta-2,3-dien-1-one (**1a**, 1 mmol) and bromoacetophenone (**2a**, 1 mmol) were added TBAF·3H₂O (2 mmol) and water (4 mL). The mixture was stirred at 80 °C for 2 h. It was then cooled to room temperature and extracted with diethyl ether (5 mL × 3). The combined organic phases were dried, filtered and concentrated under vacuum. The residue was purified by column chromatography on silica gel eluted with ethyl acetate/hexane (5–10%) to give 2-aceto-1,4-diphenylbutane-1,4-dione (**3a**):^{15*a*} ¹H NMR (400 MHz, CDCl₃) δ : 2.23 (s, 3H), 3.60 (dd, $J_1 = 18.0$ Hz, $J_2 = 6.4$ Hz, 1H), 3.78 (dd, $J_1 = 18.0$ Hz, $J_2 = 6.4$ Hz, 1H), 5.29 (t, J = 6.4 Hz, 1H), 7.42–7.63 (m, 6H), 7.96 (d, J = 7.6 Hz, 2H), 8.07 (d, J = 7.6 Hz, 2H). ¹³C NMR (100 MHz, CDCl₃) δ : 29.53, 38.02, 56.81, 128.18, 128.65, 128.86, 128.98, 133.53, 133.84, 136.00, 136.09, 196.23, 196.87, 202.29. MS: m/z 281 (MH)⁺. **3b–3x** were obtained in a similar manner.

Conclusions

In summary, we have developed an efficient and sustainable synthetic pathway toward 1,3,4'-tricarbonyl compounds through tandem reaction of 1,2-allenic ketones with α -halo carbonyl compounds under the promotion of TBAF·3H₂O in water. Notable features of this process include: 1) effective generation and transformation of the proposed allenyl anions in water; 2) the unprecedented tandem reaction of 1,2-allenic ketones resulting in the otherwise difficult to obtain 1,3,4'tricarbonyl compounds; 3) remarkably enhanced reactivity and chemoselectivity by using water as the reaction medium; 4) easy recovery and effective reuse of TBAF/H₂O.

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Notes and references

- 1 B. Xu and G. B. Hammond,, Angew. Chem., Int. Ed., 2008, 47, 689.
- 2 W. B. Wang, B. Xu and G. B. Hammond, Org. Lett., 2008, 10, 3713.
- 3 L. P. Liu, B. Xu and G. B. Hammond, Org. Lett., 2008, 10, 3887.
- 4 T. Hudlicky and J. D. Price, *Chem. Rev.*, 1989, **89**, 1467.
- 5 (a) G. D. Yin, Z. H. Wang, A. H. Chen, M. Gao, A. X. Wu and Y. J. Pan, J. Org. Chem., 2008, 73, 3377; (b) S. Raghavan and K. Anuradha, Synthesis, 2003, 711; (c) A. V. Butin, Tetrahedron Lett., 2006, 47, 4113.
- 6 (a) E. J. Corey and L. S. Hegedus, J. Am. Chem. Soc., 1969, 91, 4926;
 (b) D. Seyferth and R. C. Hui, J. Am. Chem. Soc., 1985, 107, 4551;
 (c) R. Ballini, L. Barboni, G. Bosica and D. Fiorini, Synthesis, 2002, 2725;
 (d) S. Raghavan and K. Anuradha, Tetrahedron Lett., 2002, 43, 5181;
 (e) Y. Kubota, H. Nemoto and Y. Yamamoto, J. Org. Chem., 1991, 56, 7195;
 (f) Y. Nishiyama and A. Kobayashi, Tetrahedron Lett., 2006, 47, 5565.
- 7 (a) Y. Nishiyama and A. Kobayashi, *Tetrahedron Lett.*, 2006, 47, 5565; (b) T. Fujii, T. Hirao and Y. Ohshiro, *Tetrahedron Lett.*, 1992, 33, 5823; (c) L. A. Paquette, E. I. Bzowej, B. M. Branan and K. J. Stanton, *J. Org. Chem.*, 1995, 60, 7277; (d) N. De Kimpe, Z. P. Yao and N. Schamp, *Tetrahedron Lett.*, 1986, 27, 1707.
- 8 (a) D. W. Custar, H. Le and J. P. Morken, Org. Lett., 2010, 12, 3760;
 (b) P. Setzer, A. Beauseigneur, M. S. M. Pearson-Long and P. Bertus, Angew. Chem., Int. Ed., 2010, 49, 8691; (c) M. Sauthier, N. Lamotte, J. Dheur, Y. Castanet and A. Mortreux, New J. Chem., 2009, 33, 969;
 (d) A. M. Echavarren, M. Parez, A. M. Castano and J. M. Cuerva, J. Org. Chem., 1994, 59, 4179; (e) X. Lu, J. Ji, D. Ma and W. Shen, J. Org. Chem., 1991, 56, 5774; (f) S. Matsumoto, Y. Okubo and K. Mikami, J. Am. Chem. Soc., 1998, 120, 4015.
- 9 (a) S. M. Ma, S. C. Yu and S. H. Yin, J. Org. Chem., 2003, 68, 8996 and references cited therein; (b) S. M. Ma, S. C. Yu and W. J. Qian, *Tetrahedron*, 2005, 61, 4157.
- 10 H. F. Schuster and G. M. Coppola, Allenes in Organic Synthesis, Wiley, New York, 1984.
- (a) J. A. Marshall and G. S. Bartley, J. Org. Chem., 1994, 59, 7169;
 (b) S. M. Ma, J. L. Zhang and L. H. Lu, Chem.-Eur. J., 2003, 9, 2447;
 (c) C.-Y. Zhou, P. W. H. Chan and C.-M. Che, Org. Lett., 2006, 8, 325.
- 12 K. Kumar, A. Kapur and M. P. S. Ishar, Org. Lett., 2000, 2, 787.
- 13 (a) A. R. Katritzky, N. K. Meher and S. K. Singh, J. Org. Chem., 2005, 70, 7792; (b) A. Nagpal, R. Unny and Y. C. Joshi, Heterocycl. Commun., 2001, 32, 589; (c) D. Simoni, F. P. Invidiata, R. Rondanin, S. Grimaudo, G. Cannizzo, E. Barbusca, F. Porretto, N. D'Alessandro and M. Tolomeo, J. Med. Chem., 1999, 42, 4961.
- 14 (a) A. V. Kel'in, *Curr. Org. Chem.*, 2003, **7**, 1691; (b) A. V. Kel'in and A. Maioli, *Curr. Org. Chem.*, 2003, **7**, 1855.
- (a) Y. J. Liu and Y. M. Zhang, *Tetrahedron*, 2003, **59**, 8429;
 (b) A. Miyashita, A. Numata, Y. Suzuki, K.-I. Iwamoto and T. Higashino, *Chem. Lett.*, 1997, 697; (c) P.-K. Chiu and M. P. Sammes, *Tetrahedron*, 1988, **44**, 3531.
- 16 S. Narayan, J. Muldoon, M. G. Finn, V. V. Fokin, H. C. Kolbe and K. B. Sharpless, *Angew. Chem.*, *Int. Ed.*, 2005, 44, 3275.
- 17 (a) M. Lamblin, L. Nassar-Hardy, J.-C. Hierso, E. Fouquet and F.-X. Felpin, Adv. Synth. Catal., 2010, **352**, 33; (b) N. Yan, C. Xiao and Y. Kou, Coord. Chem. Rev., 2010, **254**, 1179; (c) C.-J. Li, Chem. Rev., 2005, **105**, 3095.
- 18 (a) X.-P. Fu, L. Liu, D. Wang, Y.-J. Chen and C.-J. Li, Green Chem., 2011, 13, 549; (b) K. Wang, X.-H. Bi, S.-X. Xing, P.-Q. Liao, Z.-X. Fang, X.-Y. Meng, Q. Zhang, Q. Liu and Y. Ji, Green Chem., 2011, 13, 562; (c) E. Soleimani, M. M. Khodaei, N. Batooie and M. Baghbanzadeh, Green Chem., 2011, 13, 566; (d) X.-C. Meng, H.-Y. Cheng, S.-I. Fujita, Y.-C. Yu, F.-Y. Zhao and M. Arai, Green Chem., 2011, 13, 570; (e) A. Shaabani, A. Sarvary, S. Ghasemi, A. H. Rezayan, R. Ghadari and S. W. Ng, Green Chem., 2011, 13, 582; (f) F. Godoy, C. Segarra, M. Poyatos and E. Peris, Organometallics, 2011, 30, 684; (g) A. Ohtaka, T. Teratani, R. Fujii, K. Ikeshita, T. Kawashima, K. Tatsumi, O. Shimomura and R. Nomura, J. Org. Chem., 2011, 76, 4052.
- 19 (a) A. K. Chakraborti, S. Rudrawar, K. B. Jadhav, G. Kaur and S. V. Chankeshwara, *Green Chem.*, 2007, **9**, 1335; (b) N. Parikh, D. Kumar, S. R. Roy and A. K. Chakraborti, *Chem. Commun.*, 2011, **47**, 1797; (c) G. L. Khatik, R. Kumar and A. K. Chakraborti, *Org. Lett.*, 2006, **8**, 2433; (d) S. V. Chankeshwara and A. K. Chakraborti, *Org. Lett.*, 2006, **8**, 3259.