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Visible light photocatalysis with CBr₄: a highly selective aerobic photooxidation of methylarenes to aldehydes⁺

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A metal-free, operationally simple and efficient means of aerobic photooxidation of methylarenes to aromatic aldehydes at room temperature employing visible light photocatalysis with CBr₄ is reported. The reaction is highly selective as it proceeds without any over oxidation to carboxylic acids. The utilisation of visible light and molecular oxygen is inexpensive, readily available, non-toxic and the sustainable reagents make the protocol compatible with green chemistry demands. A plausible mechanism for the formation of aldehydes from methylarenes is also provided.

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Introduction

The fundamental objective of chemists is to develop new sustainable routes for chemical transformations having significant conceptual and practical interest under mild reaction conditions.1 In this context, visible light-mediated photoredox catalysis has emerged as a state-of-the-art alternative to advance this goal.² In recent years, visible light-induced synthetic methodologies have received central attention from various research groups, especially because of its eco-compatibility, easy availability, safe handling and everlasting abundance as an energy source.3 Consequently, a number of synthetic protocols have been developed that utilise the powerful photocatalytic properties of highly expensive and potentially toxic ruthenium and iridium complexes. Therefore, the development of synthetically useful chemical transformations employing inexpensive visible light photocatalysts would be warmly welcomed, especially in terms of economical and environmental issues.

Among various methods, oxidation reactions having unique advantage to activate inert bonds, especially C–H bonds, play a pivotal role in the chemical industry for designing and realising the chemical intermediates and fine chemical specialties.^{4,5} However, selectivity of oxidation is still an open challenge for chemists. Similarly, carbonyl compounds, the vital substrates in organic synthesis,^{6,7} are still synthesized by noneco-compatible methods with very low atom economy involving copious amount of waste generation. Hence, selective oxidation of methylarenes to synthetically important carbonyl compounds is quite demanding concerning both reactivity and selectivity issues.

Traditionally, inorganic oxidizing agents like chromates, permanganates and cerrates, employed in stoichiometric amounts, suffer from noxious heavy-metal waste generation and their outlay.⁸ Therefore, development of a cleaner and costeffective methodology would be a valuable contribution to this industrially important field.

In contrast to traditional methods several transition-metal based catalytic processes using selenium,9 silver10 and copper¹¹ metal catalysts have also been reported for selective oxidation of methylarenes. Though these metal catalysts are very effective for selective oxidation, most of them are very expensive and hazardous to the environment. To overcome the hazards associated with metal catalysts, several non-metallic catalytic pathways for selective oxidation of methylarenes were reported viz. 9,10-dicyanoanthracene/methyl viologen and oxygen mediated photocatalysis12 and enzyme laccase/ABTS,8 DDQ/NBS,¹³ H₂O₂/HBr,¹⁴ Br₂/DMSO¹⁵ or IBX/DMSO¹⁶ catalysis but these processes also suffer from one or more drawbacks of substrate limitations, handling problems, poor selectivity and yield issues. Hence, development of a metal-free, environmentally benign, cost effective and sustainable method for selective oxidation of methylarenes is necessarily a welcome move.

Recently, a stoichiometric amount of CBr_4 has been used to generate bromine free radicals under visible light irradiation in several synthetically useful reactions.^{18d,19b} We reasoned that a photoreaction employing CBr_4 as a source of bromine radicals and producing HBr as a by-product could be rendered catalytic with respect to CBr_4 in the presence of an oxidant which *in situ* regenerates the bromine free radical from HBr.

Inspired by the aforementioned facts and our continued efforts to devise metal-free efficient synthetic routes,¹⁸ we hypothesised visible light-mediated one-pot selective oxidation of methylarenes up to aromatic aldehydes only employing CBr₄

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Previous work:

(a) Ananthakrishnan and Gazi 17



Scheme 1 Visible light-assisted oxidation of methylarenes to aldehydes.

as a photocatalyst and molecular oxygen as an oxidant (Scheme 1c). Implication of visible light and molecular oxygen as reagents makes the protocol greener, more viable and sustainable than existing methodologies. Moreover, visible light is a traceless reagent and oxygen is believed to generate water as the sole by-product. The present protocol on selective oxidation of methylarenes being inexpensive, metal-free, employing economical acquisition of reagents would be a valuable addition to this field.⁷ A plausible mechanistic pathway for the selective oxidation of methylarenes to aldehydes is given in Results and Discussion Section.

Results and discussion

To realise our hypothesis and determine the optimal reaction conditions, we materialised the study with a model reaction of toluene (1a, 1 mmol) with catalytic amount of CBr_4 (2, 10 mol%) in acetonitrile under an oxygen atmosphere (O₂ balloon) and visible light irradiation using 18 W CFL (380-740 nm) for 2 h at rt. To our delight, the desired product benzaldehyde (3a) was obtained as the sole product in an excellent yield of 89%. With this encouraging result, we performed a series of control and screening experiments and firstly observed that the reaction did not proceed in the dark (Table 1, entry 2). Similarly, the absence of CBr₄ under the reaction conditions leads to the same conclusion (Table 1, entry 3). These results suggest the necessity of both light and CBr₄ for the reaction. Next, to determine the role of oxygen, the screening was performed under degassed condition and an inert argon atmosphere (Table 1, entries 4 and 5) and the results revealed that the molecular oxygen is equally essential for the present oxidation reaction. The system also worked under an air atmosphere instead of an oxygen balloon

| Table 2 | Optimization of solvent ^a | | |
|---------|--------------------------------------|----------|-----------|
| Entry | Solvent | Time (h) | Yield (%) |
| 1 | CH ₃ CN | 2 | 89 |
| 2 | CH ₃ OH | 8 | 40 |
| 3 | CH ₃ CH ₂ OH | 8 | 38 |
| 4 | ^t BuOH | 8 | 27 |
| 5 | Hexane | 8 | 35 |
| 6 | THF | 8 | 18 |

^{*a*} Reaction conditions: toluene (1a, 1.0 mmol) and CBr_4 (2, 10 mol%) in a solvent (3 mL) were irradiated under a molecular oxygen atmosphere at rt using 18 W CFL for 2–8 h.



| Entry | Reaction conditions | Irradiation time (h) | Yield ^{b} (%) |
|----------------|--------------------------------------------------------------|----------------------|-------------------------------------|
| 1 | CBr ₄ (10 mol%). O ₂ halloon, 18 W CFL | 2 | 89 |
| 2^{c} | CBr_4 (10 mol%), O_2 balloon, in the dark | - 8 | nd |
| 3 | Without CBr ₄ , O ₂ balloon, 18 W CFL | 8 | nd |
| 4^d | CBr ₄ (10 mol%), degassed, 18 W CFL | 8 | nd |
| 5 ^e | CBr_4 (10 mol%), argon, 18 W CFL | 8 | nd |
| 6 | CBr ₄ (10 mol%), air, 18 W CFL | 4 | 62 |
| 7 | CBr_4 (5 mol%), O_2 balloon, 18 W CFL | 4 | 45 |
| 8 | CBr_4 (15 mol%), O_2 balloon, 18 W CFL | 2 | 89 |
| 9 | NBS (10 mol%), O ₂ balloon, 18 W CFL | 18 | 26 |
| 10 | BDMS (10 mol%), O ₂ balloon, 18 W CFL | 18 | 6 |

^{*a*} Reaction conditions: toluene (**1a**, 1.0 mmol) and CBr₄ (**2**, 10 mol%) in CH₃CN (3 mL) were irradiated under a molecular oxygen atmosphere (O₂ balloon) at rt using 18 W CFL for 2–18 h. ^{*b*} Isolated yield of the product **3a**; nd = not detected. ^{*c*} Reaction was carried out in the dark. ^{*d*} Reaction was carried out under degassed condition. ^{*e*} Reaction was carried out under an argon atmosphere.





^{*a*} For general procedure, see ESI. ^{*b*} All compounds are known and were characterized by comparison of their spectral data with those reported in the literature (see ESI).^{*c*,20} ^{*c*} Isolated yield of purified products **3**.

but delivered a considerably lower yield of 3a (Table 1, entry 6). Cumulatively, on decreasing the amount of CBr₄ from 10 mol% to 5 mol%, the yield of 3a was significantly reduced (Table 1, entry 1 vs. 7). However, use of 15 mol% CBr₄ did not affect the yield of the product (Table 1, entry 8). Other bromine sources, viz. NBS, and BDMS (bromodimethylsulfonium bromide) did not work satisfactorily under the present reaction conditions (Table 1, entries 1 vs. 9 and 10).

Given the importance of solvent activity in chemical transformations, we performed a series of experiments for optimization. The results reveal the superiority of acetonitrile over the other tested solvents, viz. CH₃OH, CH₃CH₂OH, ^tBuOH, hexane and THF (Table 2, entry 1 vs. 2-6).

Having established the optimal reaction conditions for visible light-mediated oxidation of methylarenes, we surveyed the generality and scope of the present protocol over a wide range of methylarenes (Table 3).

In general, methylarenes bearing either an electron-donating (Me or OMe) or an electron-withdrawing substituent (NO2, F, Cl, Br, I, CN, MeSO₂, PhSO₂, CONH₂, COOEt or COPh) are well tolerated in the present methodology and afford carbonyl compounds in good to excellent yields of 75-96%. However, methylarenes bearing an electron-donating substituent on the aromatic ring appear to react faster and afford marginally higher yield than those bearing an electron-withdrawing group. Also, evaluation of aliphatic hydrocarbons in the present methodology does not lead to the satisfactory results probably



Scheme 2 Quenching of the reaction with TEMPO.



Scheme 3 Plausible mechanism for the visible light-promoted aerobic oxidation of methylarenes to aldehydes.

due to the far less stability of an alkyl radical than a benzyl radical.

Congruent with the above observations and the literature precedents,17,19 a plausible mechanism for the visible light and CBr₄-promoted selective oxidation of methylarenes to aromatic aldehydes is depicted in Scheme 3. The mechanism might follow a radical pathway, as on addition of TEMPO (2,2,6,6tetramethyl-1-piperidinyloxyl), a traditional radical scavenger, the reaction was quenched (Scheme 2) and that the formation of benzyl-TEMPO adduct was confirmed by its MS (HRMS (EI) calcd for C₁₆H₂₅NO: 247.1936, found 247.1934). On irradiation with visible light using 18 W CFL under a molecular oxygen environment, CBr₄ generates the bromine radical, which reacts with methylarene 1 to form resonance stabilised benzyl radical 4 along with HBr. The benzyl radical 4 combines with O_2 to generate peroxy radical 5. The peroxy radical 5 abstracts hydrogen atom from HBr and regenerates the bromine radical along with the hydroperoxide 6, which eliminates H₂O to afford the desired product 3.

Conclusion

In conclusion, we have developed a novel, highly efficient, metal-free, one-pot synthesis of aromatic aldehydes by aerobic oxidation of methylarenes employing visible light photocatalysis with CBr₄. Notably, water is the only by-product in the reaction. The protocol overrides the other methods for highly selective oxidation of methylarenes only up to the aldehyde stage. Advantageously, it utilises visible light and molecular oxygen as clean, inexpensive and sustainable reagents and does not require any additives, heating or inert conditions.

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References and notes

- 1 C. Dai, J. M. R. Narayanam and C. R. J. Stephenson, Nat. Chem., 2011, 3, 140.
- 2 For leading reviews on visible light photoredox catalysis, see: (a) K. Zeitler, Angew. Chem., Int. Ed., 2009, 48, 9785; (b) T. P. Yoon, M. A. Ischay and J. Du, Nat. Chem., 2010, 2, 527; (c) F. Teply, Collect. Czech. Chem. Commun., 2011, 76, 859; (d) J. M. R. Narayanam and C. R. J. Stephenson, Chem. Soc. Rev., 2011, 40, 102; (e) J. Xuan and W.-J. Xiao, Angew. Chem., Int. Ed., 2012, 51, 6828; (f) Y. Xi, H. Yia and A. Lei, Org. Biomol. Chem., 2013, 11, 2387; (g) C. K. Prier, D. A. Rankic and D. W. C. MacMillan, Chem. Rev., 2013, 113, 5322; (h) D. M. Schultz and T. P. Yoon, Science, 2014, 343, 1239176.
- 3 (a) G. Ciamician, Science, 1912, 36, 385; (b) A. Albini and M. Fagnoni, ChemSusChem, 2008, 1, 63.
- 4 (a) J. A. Labinger and J. E. Bercaw, Nat. Chem., 2002, 417, 507; (b) R. A. Sheldon and H. van Bekkum, Fine Chemicals through Heterogeneous Catalysis, Wiley-VCH, Weinheim, 2001, p. 1;

(c) J. M. Thomas, R. Raja, G. Sankar and R. G. Bell, *Nature*, 1999, **398**, 227.

- 5 (a) A. D. Sadow and T. D. Tilley, Angew. Chem., Int. Ed., 2003,
 42, 803; (b) C. Limberg, Angew. Chem., Int. Ed., 2003, 42, 5932;
 (c) S. S. Stahl, Angew. Chem., Int. Ed., 2004, 43, 3400; (d)
 B. B. Sarma, I. Efremenko and R. Neumann, J. Am. Chem. Soc., 2015, 137, 5916.
- 6 (a) F. Bruhne and E. Wright, Industrial Organic Chemicals: Starting Materials and Intermediates – An Ullmann's Encyclopedia, Wiley-VCH, Weinheim, Germany, 1999, p. 673, and references cited therein; (b) R. A. Sheldon, I. W. C. E. Arends, G. J. Brink and A. Dijksman, Acc. Chem. Res., 2002, 35, 774.
- 7 (a) Y. Xie, W. Mo, D. Xu, Z. Shen, N. Sun, B. Hu and X. Hu, J. Org. Chem., 2007, 72, 4288; (b) C. X. Miao, L. N. He, J. L. Wang and F. Wu, J. Org. Chem., 2010, 75, 257; (c) M. Tabata, K. Moriyama and H. Togo, Eur. J. Org. Chem., 2014, 3402.
- 8 A. Potthast, T. Rosenau, C. L. Chen and J. S. Gratzl, *J. Org. Chem.*, 1995, **60**, 4320.
- 9 (a) D. H. R. Barton, R. A. H. F. Hui, D. J. Lester and S. V. Ley, *Tetrahedron Lett.*, 1979, 20, 3331; (b) D. H. R. Barton and T. Wang, *Tetrahedron Lett.*, 1994, 35, 5149.
- 10 (a) R. G. R. Bacon and J. R. Doggart, J. Chem. Soc., 1960, 1332;
 (b) H. Firouzabadi and P. Salehi, Synth. Commun., 1991, 21, 1121.
- 11 (a) M. V. Bhatt and P. T. Perumal, *Tetrahedron Lett.*, 1981, 22, 2605; (b) M. P. Gore, S. J. Gould and D. D. Weller, *J. Org. Chem.*, 1992, 57, 2774.
- 12 J. Santamaria and R. Jroundi, *Tetrahedron Lett.*, 1991, 32, 4291.
- 13 H. Lee and R. G. Harvey, J. Org. Chem., 1988, 53, 4587.
- 14 M. Ghaffarzadeh, M. Bolourtchian, K. Taber-Heydar, I. Daryaei and F. Mohsenzaheh, *J. Chem. Sci.*, 2009, **121**, 177.

- 15 M. Ghaffarzadeh, M. Bolourtchian, M. Gholamhosseni and F. Mohsenzaheh, *Appl. Catal., A*, 2007, **333**, 131.
- 16 K. C. Nicolaou, T. Montagnon, P. S. Baran and Y. L. Zhong, J. Am. Chem. Soc., 2002, 124, 2245.
- 17 S. Gazi and R. Ananthkrishnan, RSC Adv., 2012, 2, 7781.
- 18 (a) A. K. Yadav, V. P. Srivastava and L. D. S. Yadav, New J. Chem., 2013, 37, 4119; (b) A. K. Yadav and L. D. S. Yadav, Tetrahedron Lett., 2014, 55, 2065; (c) T. Keshari, V. K. Yadav, V. P. Srivastava and L. D. S. Yadav, Green Chem., 2014, 16, 3986; (d) T. Keshari, V. P. Srivastava and L. D. S. Yadav, RSC Adv., 2014, 4, 5815; (e) R. Chawla, A. K. Singh and L. D. S. Yadav, Eur. J. Org. Chem., 2014, 2032; (f) A. K. Singh, R. Chawla and L. D. S. Yadav, Tetrahedron Lett., 2015, 56, 653; (g) S. Tripathi, S. N. Singh and L. D. S. Yadav, Tetrahedron Lett., 2015, 56, 4211.
- 19 (a) K. Ohkubo, K. Mizushima and S. Fukuzumi, *Res. Chem. Intermed.*, 2013, 39, 205; (b) Y. Nishina, B. Ohtani and K. Kikushima, *Beilstein J. Org. Chem.*, 2013, 9, 1663.
- 20 (a) R. L. Shriner, R. C. Fusion, D. Y. Curtin and T. C. Morrill, The Systematic Identification of Organic Compounds, 6th ed, 1980; (b) S. T. M. Ali, E. Lourdusamy and S. Arumugan, J. Org. Chem., 2006, 71, 5043; (c) C. Lin and T. Lu, Tetrahedron, 2010, 66, 9688; (d) A. N. Bandna and P. Das, Tetrahedron Lett., 2011, 52, 4954; (e) K. Layek, H. Maheswaran, R. Arundhathi, M. L. Kantam and S. K. Bhargava, Adv. Synth. Catal., 2011, 353, 606; (f) Y. Huang, X. Fang, X. Lin, W. He, Y. Yuan, Z. Weng, H. Li and K. Huang, Tetrahedron, 2012, 68, 9949; (g) P. Wang, J. Yang, L. Li, H. Hu, J. Cai, C. Sun and M. Jin, Tetrahedron Lett., 2013, 54, 533; (h) I. Masataka, M. Katsuhiko and T. Hideo, Tetrahedron, 2013, 69, 2961; (i) Z. Li, W. Zhu, J. Bao and X. Zou, Synth. Commun., 2014, 44, 1155.