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A practical, chemoselective approach to O-methylation of carboxylic acids with dimethyl malonate

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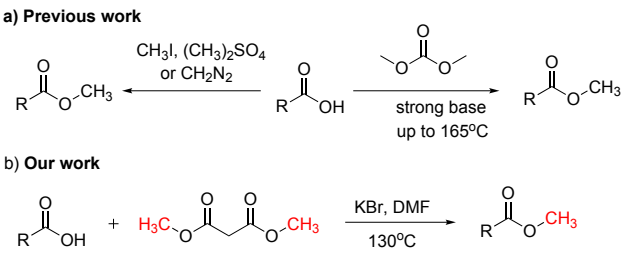
ABSTRACT

A practical and chemoselective method is described for the O-methylation of carboxylic acids. Dimethyl malonate, a low toxic and commercially available compound was found to be an effective methylating reagent for a variety of carboxylic acids affording methyl ester products in good to high yields and with excellent chemoselectivity, without the use of strong bases as additives. A mechanism involving the utilization of potassium bromide is tentatively proposed.

1. Introduction

Methylation is a crucial organic transformation in numerous processes of chemical and biological synthesis and in industry.[1] The development of methodology for practical methylation of nucleophilic substrates involving important natural products has attracted intensive attention over the past decades,[2–5] and some efficient reagents for mild, clean methylation of various substrates were introduced. Amongst them, however, several methylating reagents such as methyl iodide,[3] dimethyl sulfate,[4] and diazomethane[5] that were commonly used suffer from not only high toxicity and poor safety, but also low reactivity in the absence of extra strong alkalis during the reaction (Scheme 1). In recent years, dimethyl carbonate (DMC), an alternative to those toxic methylating agents has been developed.[6–18] DMC is a nontoxic, inexpensive, and 'green' methylating reagent, and has been extensively explored in the methylation of phenol[7] or NH-containing heteroaromatic[8] substrates. However, strong bases including both inorganic[9] and organic bases[10] or acidic compounds[11] were generally required to achieve reasonable reaction rates, and weaker bases are usually considered to be inactive to this reaction due to their disability in deprotonating the nucleophiles.[12]



Scheme 1. O-methylation of carboxylic acids.

O-Methylation or the methyl esterification of carboxylic acids is popularly used in many chemical processes including the synthesis of natural products, medicines and polymers, and the protection of functional groups.[13] Except for the toxic methylating reagents described above, the 'green' DMC has also been reported to promote the O-methylation of a range of carboxylic acids.[14] However, the substrates were limited to only electron-rich carboxylic acids and harsh reaction conditions (>150 °C high temperature, autoclave reactor and strong bases) were usually employed.[15] Besides, the

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chemoselective methylation of carboxylic acid substrates bearing hydroxyl or amino groups is still a challenging issue for synthetic chemists.[16,17] Therefore, this methodology has not been considered to be practical for a large-scale application in industry of synthetic chemistry.[18]

We have been recently dedicated to developing new chemical reactions for the modification of functionalized carboxylic acid derivatives, in particular cinnamic acid.[19] and have reported a copper-catalyzed, *tert*-butyl hydroperoxide (TBHP)-mediated methyl esterification of a broad range of substrates including benzylic alcohols, aldehydes and carboxylic acids.[20] During the course of searching new methylating reagents for the practical methyl esterification of carboxylic acids, we observed that dimethyl malonate (DMM), a methyl ester analogue of DMC, enabled efficient O-methylation of a broad scope of carboxylic acids with excellent chemoselectivity under relatively milder reaction conditions (Scheme 1).

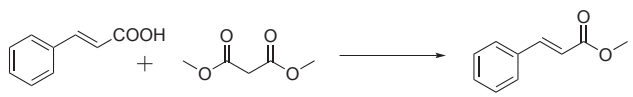
Herein, we report for the first time on the use of DMM as a low toxic, commercially available methylating reagent for the practical O-methylation of carboxylic acids under neutral conditions. High yields were achieved for a variety of aromatic or heteroaromatic carboxylic acid substrates in the presence of potassium bromide at 130 °C and excellent chemoselectivity was found for carboxylic acids bearing phenol, amine or amide functional groups.

2. Results and discussion

Initially, we chose cinnamic acid as a model compound to study the O-methylation reaction by using DMM as a methylating reagent. It was pleasing to find that the reaction between cinnamic acid and DMM proceeded in the presence of a traditional inorganic base, Na_2CO_3 in *N*,*N*-dimethyl formide (DMF) at 130 °C, affording methyl cinnamate (**3a**) in 61% yield after 12 h (entry 1, Table 1). This indicates that DMM could behave as a methylating reagent similar to DMC that was previously investigated. Other inorganic bases such as K_2CO_3, Cs_2CO_3, $NaHCO_3$ and K_2HPO_4 also promoted the O-methylation reactions of cinnamic acid with DMM, while only $NaHCO_3$ was found to improve the yield of ester to 81% (entries 2–5, Table 1). Similar to DMC-mediated methylation, the added bases might be also crucial in the present reaction, as no reaction was detected when the reaction was performed in the absence of a base (entry 6, Table 1). Further screening of the reaction conditions, however, suggested that the inorganic base additives were actually unnecessary for the DMM-directed reaction. Surprisingly, when a neutral salt, potassium iodide (KI, 20 mol %) was used to replace the inorganic bases, **3a** was obtained in 88% isolated yield after heating the reactants at 130 °C for 12 h in DMF (entry 7, Table 1). In order to further improve the yield of **3a**, other potassium or sodium halides were introduced with a 20 mol % loading amount to the reaction between cinnamic acid and DMM at 130 °C, and the resultant yields are all between 70–90% (entries 8–11, Table 1). Slightly lowering the temperature to 120 °C drastically decreases the yield in the case using NaI as a promotor (56% vs 84%, entry 12). Interestingly, increasing the loading of KBr from 20 mol % to 30 mol % was confirmed to be crucial to complete the reaction, and at this end a 96% yield was achieved (entry 13, Table 1). The solvent effect was also screened and the results revealed that DMF acted as the best solvent for this reaction (entries 14–17, Table 1). It was found that NaI also promoted a complete conversion of cinnamic acid even at 120 °C, although a much higher loading (1.0 equiv) was required (entry 18, Table 1).

With the optimized protocol in hand for the facile O-methylation of cinnamic acid, we were next interested to expand the substrate scope by varying the substituents on the aromatic ring of cinnamic acid. The related results are summarized in Table 2. It was found that various cinnamic acids with electron-donating groups were excellent candidates for the O-methylation reactions, generating the corresponding esters **3b**–**3h** exclusively in high yields, although the reactions of cinnamic acids with electron-withdrawing groups gave slightly lower yields (70%–84% for

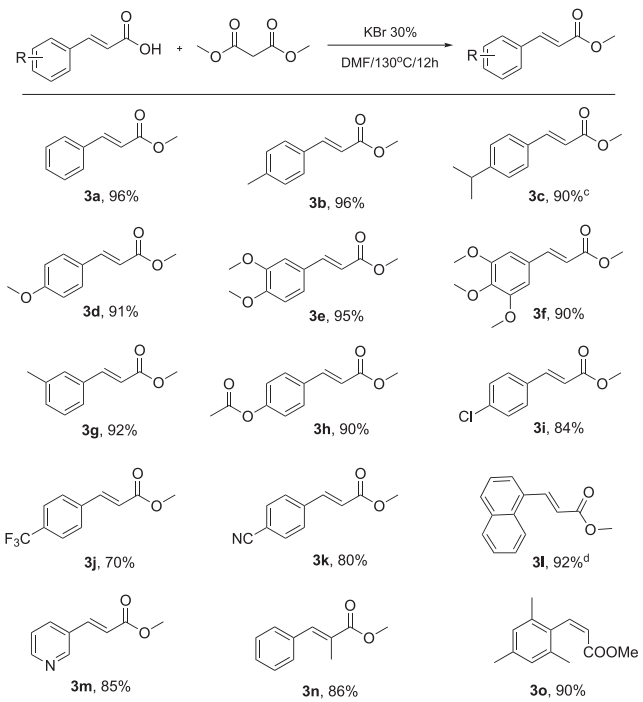
Table 1
Optimization of O-methylation of cinnamic acid with DMM[a]



Entry	Catalyst (equiv.)	Solvent	T (°C)	Conv. (%)[b]	Yield (%)[c]
1	Na_2CO_3 (0.2)	DMF	130	68	61
2	K_2CO_3 (0.2)	DMF	130	59	53
3	Cs_2CO_3 (0.2)	DMF	130	66	60
4	K_2HPO_4 (0.2)	DMF	130	32	25
5	$NaHCO_3$ (0.2)	DMF	130	88	81
6	—	DMF	130	<5	NR
7	KI (0.2)	DMF	130	92	88
8	KBr (0.2)	DMF	130	95	90
9	KF (0.2)	DMF	130	89	86
10	NaCl (0.2)	DMF	130	76	70
11	NaI (0.2)	DMF	130	88	84
12	NaI (0.2)	DMF	120	64	56
13	KBr (0.3)	DMF	130	98	96
14	KBr (0.3)	DMAc	130	85	82
15	KBr (0.3)	DMSO	130	77	73
16	KBr (0.3)	Xylene	130	26	22
17	KBr (0.3)	PhCl	130	<5	trace
18	NaI (1.0)	DMF	130	>99	98

[a] Unless otherwise stated, all reactions were carried out with **1a** (cinnamic acid: 0.3 mmol) and **2a** (DMM: 1.8 mmol, 6.0 equiv) in the air, 12 h.
[b] GC-yield.
[c] Isolated yield.

Table 2
The scope of the O-methylations[a]



[a] Reaction conditions: **1a** (cinnamic acid 0.3mmol), **2a** (dimethyl malonate 1.8mmol), KBr (30mol%), DMF 2 mL, 130 °C, 12 h, in air. [b] Isolated yield. [c] 16 h. [d] 18 h.

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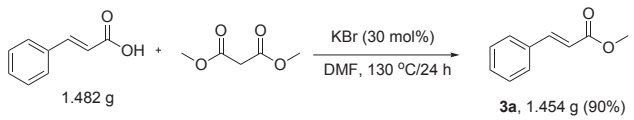
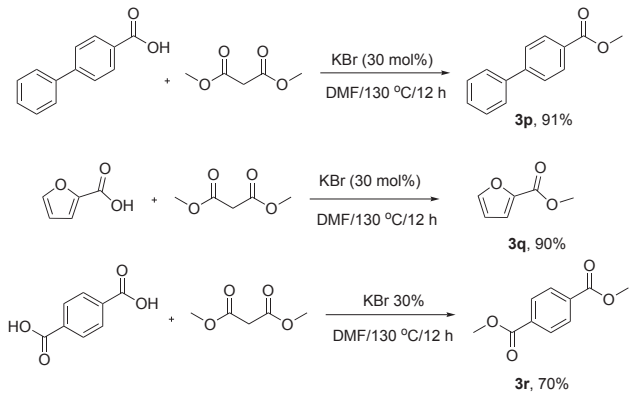
3i–**3k**). In addition, the O-methylation reaction of (*E*)-3-(naphthalen-1-yl)acrylic acid also resulted in the isolation of the desired product **3l** in 92% yield. The heterocyclic *trans*-3-(pyridin-3-yl) acrylic and acid was tolerated under the standard conditions, affording 3m in 85% yield. It was also found that α-methylcinnamic acid can be proceeded well with the methylation product **3n** isolated in 86% yield. Delightfully, except for the substrates with a *trans*-configuration depicted above, *cis*-substrate is equally effective. Thus, the reaction of a bulky substrate with a *cis*-configuration, (*Z*)-3-mesitylacrylic acid provided the corresponding ester product **3o** in a high yield (90%), with the retention of the *cis*-configuration.

It is worth noting that the present methodology is readily scaled up and represents a practical route to prepare methyl esters of a class of carboxylic acids. For example, cinnamic acid in a gram scale (1.482 g) was subjected to react with DMM under the optimized conditions for 24 h (Scheme 2), fine white solid of **3a** (1.454 g, 90%) was then obtained after a facile purification procedure (by flash column chromatograph).



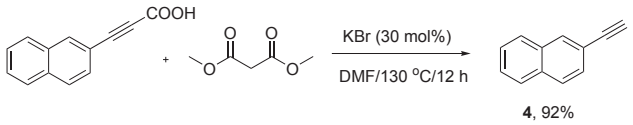
Scheme 2. 1-Gram scale synthesis of methyl cinnamate ester **3a**.

Except for cinnamic acids, other kind of aromatic carboxylic acids could also be transformed to the corresponding methyl esters in high yields as illustrated in Scheme 3. 4-Phenyl benzoic acid worked well under standard conditions, giving the ester **3p** in 91% yield. Heterocyclic esters **3q** could also be prepared in high yield by the efficient methylation of 2-furoic acid using DMM. In addition, terephthalic acid, a substrate containing two carboxylic acid groups favored methylation of both carboxylic acid units in the presence of excess amount of DMM and pure bis-methylated product **3r** was afforded in a good yield. However, this protocol was not applicable for aromatic propiolic acids, and when 3-(naphthalen-2-yl)propiolic acid were used as a substrate, an unexpected compound **4** resulting from the decarboxylation reaction was isolated as the only product in 92% yield (Scheme 4).



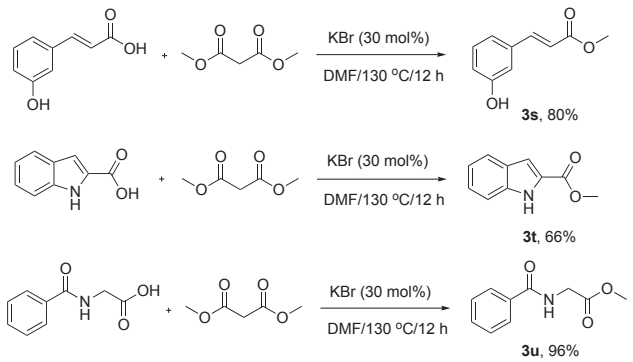
Scheme 3. Reactions of aromatic carboxylic acids with DMM.

The chemoselectivity for the DMM-mediated O-methylation of carboxylic acids was next investigated. Several represented carboxylic acid substrates incorporating a second nucleophilic functional group such as hydroxyl, amine or amide were tested and encouraging results were obtained, which are shown in Scheme 5. It was demonstrated that the substrate bearing both carboxylic acid



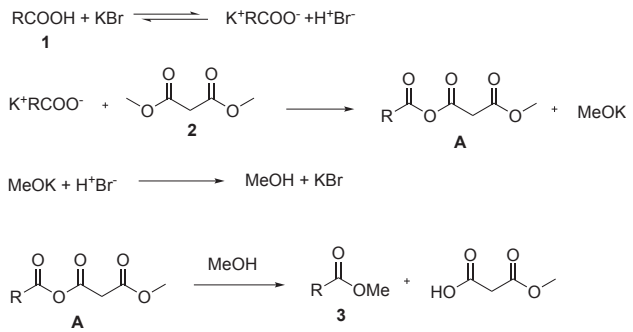
Scheme 4. The decarboxylation of 3-(naphthalen-2-yl)propiolic acid with DMM.

and phenol was selectively methylated on the carboxyl-O position, resulting in the isolation of **3s** as the only product in 80% yield when the reaction was performed under standard conditions. 1*H*-indole-2-carboxylic acid having an additional amine group was also converted to the *O*-methylated product **3t** selectively, remaining the amine unreacted, although the yield (66%) dropped slightly. Interestingly, an *N*-protected amino acid, *N*-benzoylglycine was confirmed to be a good candidate for the selective methylation, and the amide-containing ester product **3u** was harvested in an excellent yield (96%). The results presented here are remarkable, as selective methylation of carboxylic acids was scarcely approached by known methylation strategies in the literature.[13–17]



Scheme 5. Chemoselectivity test for DMM-mediated O-methylation.

Based on the previous reports on the DMC-mediated methylation and relevant mechanistic studies,[16,18] and our own findings in this work, we proposed a possible mechanism for the KBr-promoted O-methylation of carboxylic acids with DMM (Scheme 6). Initially, the *O*-nucleophile of carboxylate resulting from the equilibrium reaction between carboxylic acid 1 and KBr readily attacks the methyl group of DMM, forming a key intermediate A with the release of potassium methoxide. A then reacts with methanol that was generated from the reaction of HBr and potassium methoxide, both available from the previous steps, to produce the final ester product **3** by a nucleophilic substitution under heating condition.



Scheme 6. A proposed mechanism for DMM-mediated methylation.

3. Conclusions

In conclusion, in this work an efficient and practical method for the O-methylation of carboxylic acids has been developed by utilizing a new inexpensive and low toxic methylating reagent, dimethyl malonate. The protocol was proved to tolerate to a broad scope of substrates including cinnamic acids with electron-withdrawing or electron-donating groups, aromatic or heterocyclic carboxylic acids, and other functionalized carboxylic acids. Excellent chemoselectivity was achieved for carboxylic acids bearing additional hydroxyl, amine or amide groups. This work provides an alternative 'greener' approach to the selective O-methylation of a variety of carboxylic acids.

4. Experiment

4.1. General information

All reactions were carried out under an air atmosphere condition. various carboxylic acids, bases and salts were purchased from Aldrich, Acros or Alfa. Column chromatography was generally performed on silica gel (100–200 mesh) and reactions were monitored by thin layer chromatography (TLC) using UV light (254 nm) to visualize the course of the reactions. The ^{1}H (400 MHz) and ^{13}C NMR (100 MHz) data were recorded on Bruker 400 M Digital NMR Spectrometer using $CDCl_3$ as solvent. The chemical shifts (δ) are reported in parts per million and coupling constants (J) in Hertz. ^{1}H NMR spectra was recorded with tetramethylsilane (δ=0.00 ppm) as internal reference; ^{13}C NMR spectra was recorded with $CDCl_3$ (δ=77.500 ppm) as internal reference. All of ESI-MS were performed by the State-authorized Analytical Center in Soochow University.

4.2. General procedure for KBr-mediated methylation of carboxylic acid with dimethyl malonate

To a Schlenk tube equipped with a magnetic stir bar were added under air, carboxylic acid (0.3 mmol), dimethyl malonate (1.8 mmol) and KBr (0.09 mmol) in DMF (2 mL). The resultant reaction mixture was kept stirring at the required temperature for 12 h. After indicated reaction time, the mixture was cooled down to room temperature. It was poured into ethyl acetate, then washed with water, extracted with ethyl acetate, dried by anhydrous Na_2SO_4, then filtered and evaporated under vacuum, the residue was purified by flash column chromatography (petroleum ether or petroleum ether/ethyl acetate) to afford the corresponding coupling products with high purity.

*4.2.1. Methyl cinnamate (**3a**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.72 (d, J=16.0 Hz, 1H), 7.55–7.53 (m, 2H), 7.41–7.39 (m, 3H), 6.47 (d, J=16.0 Hz, 1H), 3.83 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.4, 144.8, 134.3, 130.3, 128.9, 128.1, 117.8, 51.7; MS (m/z) calcd for $C_{10}H_{11}O_2$ 163.1, found 163.1 $(M+H)^+$.

*4.2.2. (E)-Methyl 3-p-tolylacrylate (**3b**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.67 (d, J=16.0 Hz, 1H), 7.42 (d, J=8.0 Hz, 2H), 7.19 (d, J=8.0 Hz, 2H), 6.40 (d, J=16.0 Hz, 1H), 3.80 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.6, 144.9, 140.7, 131.7, 129.6, 128.1, 116.7, 51.6, 21.5; MS (m/z) calcd for $C_{11}H_{13}O_2$ 177.1, found 177.1 $(M+H)^+$.

*4.2.3. (E)-Methyl 3-(4-isopropylphenyl)acrylate (**3c**).* Pale yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.71 (d, J=16.0 Hz, 1H), 7.48 (d, J=8.2 Hz, 2H), 7.27 (d, J=8.2 Hz, 2H), 6.43 (d, J=16.0 Hz, 1H), 3.82 (s, 3H), 3.00–2.90 (m, 1H), 1.28 (d, J=7.2 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.7, 151.6, 144.9, 132.0, 128.2, 127.0, 116.8, 51.7, 34.10, 23.8; MS (m/z) calcd for $C_{13}H_{17}O_2$ 205.1, found 205.1 $(M+H)^+$.

*4.2.4. (E)-Methyl 3-(4-methoxyphenyl)acrylate (**3d**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.66 (d, J=16.0 Hz, 1H), 7.48 (d, J=8.8 Hz, 2H), 6.91 (d, J=8.8 Hz, 2H), 6.32 (d, J=16.0 Hz, 1H), 3.84 (s, 3H), 3.80 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.8, 161.4, 144.5, 129.7, 127.1, 115.2, 114.3, 55.4, 51.6; MS (m/z) calcd for $C_{11}H_{13}O_3$ 193.1, found 193.1 $(M+H)^+$.

*4.2.5. (E)-Methyl 3-(3,4-dimethoxyphenyl)acrylate (**3e**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.61 (d, J=16.0 Hz, 1H), 7.09–7.07 (dd, J=8.4, 2.0 Hz, 1H), 7.02 (d, J=2.0 Hz, 1H), 6.84 (d, J=8.0 Hz, 1H), 6.29 (d, J=16.0 Hz, 1H), 3.89 (s, 6H), 3.77 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.7, 151.1, 149.2, 144.8, 127.3, 122.6, 115.5, 111.0, 109.6, 55.9, 55.9, 51.6; MS (m/z) calcd for $C_{12}H_{15}O_4$ 223.1, found 223.1 $(M+H)^+$.

*4.2.6. (E)-Methyl 3-(3,4,5-trimethoxyphenyl)acrylate (**3f**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.60 (d, J=16.0 Hz, 1H), 6.75 (s, 2H), 6.34 (d, J=16.0 Hz, 1H), 3.88 (s, 6H), 3.87 (s, 3H), 3.80 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.4, 153.4, 144.8, 140.1, 129.9, 117.0, 105.2, 60.9, 56.1, 51.7; MS (m/z) calcd for $C_{13}H_{17}O_5$ 253.1, found 253.1 $(M+H)^+$.

*4.2.7. (E)-Methyl 3-m-tolylacrylate (**3g**).* Pale yellow liquid; ^{1}H NMR (400 MHz, CDCl3) δ 7.69 (d, J=16.0 Hz, 1H), 7.35 (d, J=6.0 Hz, 2H), 7.31–7.27 (m, 1H), 7.22 (d, J=7.4 Hz, 1H), 6.45 (d, J=16.0 Hz, 1H), 3.83 (s, 3H), 2.39 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.5, 145.1, 138.6, 134.3, 131.1, 128.8, 128.7, 125.3, 117.6, 51.7, 21.3; MS (m/z) calcd for $C_{11}H_{13}O_2$ 177.1, found 177.1 $(M+H)^+$.

*4.2.8. (E)-Methyl 3-(4-acetoxyphenyl)acrylate (**3h**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=8.04 (d, J=8.4 Hz, 2H), 7.70 (d, J=16.0 Hz, 1H), 7.57 (d, J=8.4 Hz, 2H), 6.51 (d, J=16.0 Hz, 1H), 3.92 (s, 3H), 3.81 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.0, 166.5, 143.5, 138.6, 131.4, 130.1, 127.9, 120.2, 52.3, 51.9; MS (m/z) calcd for $C_{12}H_{13}O_4$ 221.1, found 221.1 $(M+H)^+$.

*4.2.9. (E)-Methyl 3-(4-chlorophenyl)acrylate (**3i**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.65 (d, J=16.0 Hz, 1H), 7.47–7.45 (m, 2H), 7.38–7.36 (m, 2H), 6.42 (d, J=16.0 Hz, 1H), 3.82 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.2, 143.4, 136.2, 132.9, 129.2, 129.2, 118.4, 51.8; MS (m/z) calcd for $C_{10}H_{10}ClO_2$ 197.1, found 197.1 $(M+H)^+$.

*4.2.10. (E)-Methyl 3-(4-(trifluoromethyl)phenyl)acrylate (**3j**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.72 (d, J=16.0 Hz, 1H), 7.68–7.62 (m, 4H), 6.53 (d, J=16.0 Hz, 1H), 3.84 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=166.8, 143.0, 137.7 (d, J=1.2 Hz, 1C), 131.8 (d, J=32.0 Hz,1C), 128.2, 125.9 (q, 1C), 123.81(d, J=272 Hz, 1C), 120.4, 51.9; MS (m/z) calcd for $C_{11}H_{10}F_3O_2$ 231.1, found 231.1 $(M+H)^+$.

*4.2.11. (E)-Methyl 3-(4-cyanophenyl)acrylate (**3k**).* White solid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=7.70–7.66 (m, 3H), 7.62 (d, J=8.4 Hz, 2H), 6.53 (d, J=16.0 Hz, 1H), 3.83 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=166.6, 142.4, 138.7, 132.7, 128.4, 121.4, 118.3, 113.4, 52.0; MS (m/z) calcd for $C_{11}H_{10}NO_2$ 188.1, found 188.1 $(M+H)^+$.

*4.2.12. (E)-Methyl 3-(naphthalen-1-yl)acrylate (**3l**).* Pale yellow liquid; ^{1}H NMR (400 MHz, $CDCl_3$) δ=8.57 (d, J=15.8 Hz, 1H), 8.22 (d, J=8.3, 1H), 7.90 (t, J=7.6 Hz, 2H), 7.77 (d, J=7.2 Hz, 1H), 7.62–7.48 (m, 3H), 6.57 (d, J=15.8 Hz, 1H), 3.89 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.3, 141.9, 133.7, 131.7, 131.4, 130.6, 128.8, 126.9, 126.3, 125.5,

125.0, 123.394, 120.5, 51.8; MS (m/z) calcd for $C_{14}H_{13}O_2$ 213.1, found 213.1 $(M+H)^+$.

*4.2.13. (E)-Methyl 3-(pyridin-3-yl)acrylate (**3m**).* Yellow solid; ^1H NMR (400 MHz, $CDCl_3$) δ=8.71 (d, J=2.0 Hz, 1H), 8.58–8.57 (dd, J=4.8 Hz, 1.6 Hz, 1H), 7.83–7.80 (m, 1H), 7.65 (d, J=16.0 Hz, 1H), 7.33–7.29 (m, 1H), 6.49 (d, J=16.0 Hz, 1H), 3.80 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=166.8, 151.0, 149.7, 141.1, 134.3, 130.2, 123.8, 120.0, 51.9; MS (m/z) calcd for $C_9H_{10}NO_2$ 164.1, found 164.1 $(M+H)^+$.

*4.2.14. (E)-Methyl 2-methyl-3-phenylacrylate (**3n**).* White solid; ^1H NMR (400 MHz, $CDCl_3$) δ=7.72 (d, J=1.6 Hz, 1H), 7.42 (d, J=4.4 Hz, 4H), 7.37–7.33 (m, 1H), 3.85 (s, 3H), 2.15 (d, J=1.6 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=169.2, 139.0, 135.9, 129.6, 128.4, 128.3, 52.1, 14.1; MS (m/z) calcd for $C_{11}H_{13}O_2$ 177.1, found 177.1 $(M+H)^+$.

*4.2.15. (Z)-Methyl 3-mesitylacrylate (**3o**).* White solid; ^1H NMR (400 MHz, $CDCl_3$) δ=7.09 (d, J=12.0 Hz, 1H), 6.90 (s, 2H), 6.18 (d, J=12.0 Hz, 1H), 3.64 (s, 3H), 2.32 (s, 3H), 2.20 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=165.8, 144.6, 136.8, 134.5, 132.6, 127.9, 122.2, 51.3, 21.1, 20.2; MS (m/z) calcd for $C_{13}H_{17}O_2$ 205.1, found 205.1 $(M+H)^+$.

*4.2.16. Methyl biphenyl-4-carboxylate (**3p**).* White solid; ^1H NMR (400 MHz, $CDCl_3$) δ=8.15–8.14 (m, 2H), 7.70–7.65 (m, 4H), 7.51–7.48 (m, 2H), 7.44–7.41 (m, 1H), 3.97 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=167.0, 145.7, 140.0, 130.1, 128.9, 128.9, 128.2, 127.3, 127.1, 52.2; MS (m/z) calcd for $C_{14}H_{13}O_2$ 213.1, found 213.1 $(M+H)^+$.

*4.2.17. Methyl furan-2-carboxylate (**3q**).* Colorless liquid; ^1H NMR (400 MHz, $CDCl_3$) δ=7.57 (d, J=0.8 Hz, 1H), 7.18 (d, J=3.6 Hz, 1H), 6.51–6.50 (dd, J=3.6 Hz, 1.8 Hz, 1H), 3.89 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=158.7, 145.8, 144.1, 117.5, 111.4, 51.4; MS (m/z) calcd for $C_6H_7O_3$ 127.1, found 127.1 $(M+H)^+$.

*4.2.18. Methyl 1H-indole-2-carboxylate (**3t**).* White solid; ^1H NMR (400 MHz, $CDCl_3$) δ=9.12 (s, 1H), 7.73 (d, J=8.0 Hz, 1H), 7.47–7.45 (dd, J=8.3 Hz, 0.7 Hz, 1H), 7.38–7.34 (m, 1H), 7.27–7.26 (m, 1H), 7.19–7.17 (m, 1H), 3.99 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=162.6, 136.9, 127.5, 127.1, 125.5, 122.7, 120.9, 111.9, 108.8, 52.1; MS (m/z) calcd for $C_{10}H_{10}NO_2$ 176.1, found 176.1 $(M+H)^+$.

*4.2.19. 2-Ethynylnaphthalene (**4**).* White solid; ^1H NMR (400 MHz, $CDCl_3$) δ=8.07 (s, 1H), 7.86–7.81 (m, 3H), 7.58–7.51 (m, 3H), 3.19 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=133.0, 132.8, 132.3, 128.6, 128.1, 127.8127.8, 126.9, 126.6, 119.4, 84.0, 77.5; MS (m/z) calcd for $C_{12}H_9$ 153.1, found 153.1 $(M+H)^+$.

*4.2.20. Dimethyl terephthalate (**3r**).* White solid; ^1H NMR (400 MHz, $CDCl_3$) δ=8.10 (d, J=0.4 Hz, 4H), 3.95 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=166.3, 133.9, 129.6, 52.4; MS (m/z) calcd for $C_{10}H_{11}O_4$ 195.1, found 195.1 $(M+H)^+$.

*4.2.21. (E)-Methyl 3-(3-hydroxyphenyl)acrylate (**3s**).* White solid; ^1H NMR (400 MHz, $CDCl_3$) δ=7.67 (d, J=16.0 Hz, 1H), 7.27 (t, J=7.5 Hz, 1H), 7.10–7.06 (m, 2H), 6.95–6.92 (m, 1H), 6.43 (d, J=16.0 Hz, 1H), 3.84 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=168.1, 156.4, 145.3, 135.7, 130.1, 120.7, 117.8, 117.8, 114.7, 52.0; MS (m/z) calcd for $C_{10}H_{11}O_3$ 179.1, found 1791 $(M+H)^+$.

*4.2.22. Methyl-2-benzamidoacetate (**3u**).* Pale yellow liquid; ^1H NMR (400 MHz, $CDCl_3$) δ=7.83–7.80 (m, 2H), 7.52–7.48 (m, 1H), 7.44–7.40 (m, 2H), 6.98 (s, 1H), 4.23–4.22 (m, 2H), 3.77 (d, J=1.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ=170.6, 167.6, 133.6, 131.8, 128.6, 127.1, 52.4, 41.7; MS (m/z) calcd for $C_{10}H_{12}NO_3$ 194.1, found 194.1 $(M+H)^+$.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2015.10.024.

References and notes

1. (a) Crosignani, S.; White, P. D.; Linclau, B. *Org. Lett.* **2002**, *4*, 1035; (b) Otera, J. *Angew. Chem., Int. Ed.* **2001**, *40*, 2044.
2. (a) Fischer, E.; Speier, A. *Chem. Ber.* **1895**, *28*, 3252; (b) Larock, R. C. Wiley-VCH: New York, 1999. (c) Heller, S. T.; Sarpong, R. *Org. Lett.* **2010**, *12*, 4572; (d) Brohmer, M. C.; Mundinger, S. M.; Bannwarth, W. *Angew. Chem., Int. Ed.* **2011**, *50*, 6175; (e) Das, S.; Bobbink, F. D.; Dyson, P. J. *Angew. Chem., Int. Ed.* **2014**, *53*, 12876; (f) Turner, R. A.; Hauksson, N. E.; Gipe, J. H.; Lokey, R. S. *Org. Lett.* **2013**, *15*, 5012; (g) Xia, Q. S.; Liu, X. L.; Chen, W. Z. *Org. Lett.* **2013**, *15*, 3326; (h) Laplante, C.; Hall, D. G. *Org. Lett.* **2001**, *3*, 1487.
3. (a) Ahmad, A. R.; Mehta, L. K.; Parrick, J. *Tetrahedron* **1995**, *51*, 12899; (b) Wang, T.; Lui, A. S. *Org. Lett.* **1999**, *1*, 1835; (c) Abbotto, A.; Bradamante, S.; Facchetti, A. *J. Org. Chem.* **1997**, *62*, 5755; (d) Tratrat, C.; Giorgi-Renault, S.; Husson, H.-P. *J. Org. Chem.* **2000**, *65*, 6773.
4. (a) Merz, A. *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 846; (b) Basak, A.; Nayak, M. K.; Chakraborti, A. K. *Tetrahedron Lett.* **1998**, *39*, 4883; (c) Voskresensky, S.; Makosza, M. *Synth. Commun.* **2000**, *30*, 3523; (d) Chakraborti, A. K.; Basak, A.; Grover, V. *J. Org. Chem.* **1999**, *64*, 8014.
5. Pizey, J. S. Horwood: New York, 1974, 2, 65.
6. (a) Mauri, M. M.; Romano, U.; Rivetti, F. Q. *Ing. Chim. Ital.* **1985**, *21*, 6; (b) Shaikh, A.-A. G.; Sivaram, S. *Chem. Rev.* **1996**, *96*, 951; (c) Selva, M.; Perosa, A. *Green Chem.* **2008**, *10*, 457.
7. (a) Lissel, M.; Schmidt, S.; Neumann, B. *Synthesis* **1986**, 382; (b) Bomben, A.; Selva, M.; Tundo, P.; Valli, L. *Ind. Eng. Chem. Res.* **1999**, *38*, 2075; (c) Tundo, P.; Trotta, F.; Moraglio, G.; Ligorati, F. *Ind. Eng. Chem. Res.* **1988**, *27*, 1565; (d) Barcelo, G.; Grenouillat, D.; Senet, J. P.; Sennyey, G. *Tetrahedron* **1991**, *46*, 1839; (e) Selva, M.; Trotta, F.; Tundo, P. *J. Chem. Soc.* **1992**, 519.
8. (a) Selva, M.; Bomben, A.; Tundo, P. *J. Chem. Soc., Perkin Trans. 1* **1997**, 1041; (b) Selva, M.; Tundo, P.; Perosa, A. J. *Org. Chem.* **2001**, *66*, 677; (c) Shieh, W.-C.; Dell, S.; Bach, A.; Blacklock, T. J. *J. Org. Chem.* **2003**, *68*, 1954.
9. (a) Lee, Y.; Shimizu, I. *Synlett* **1998**, 1063; (b) Tundo, P.; Rossi, L.; Loris, A. *J. Org. Chem.* **2005**, *70*, 2219; (c) Rajabi, F.; Saidi, M. R. *Synth. Commun.* **2004**, *34*, 4179; (d) Ouk, S.; Thiebaud, S.; Borredon, E.; Legars, P.; Lecomte, L. *Tetrahedron Lett.* **2002**, *43*, 2661; (e) Selva, M.; Tundo, P.; Perosa, A. *J. Org. Chem.* **2003**, *68*, 7374.
10. (a) Shieh, W.-C.; Lozanov, M.; Loo, M.; Repic, O.; Blacklock, T. J. *Tetrahedron Lett.* **2003**, *44*, 4563; (b) Tilstam, U. *Org. Process Res. Dev.* **2012**, *16*, 1974; (c) Laurila, M. L.; Magnus, N. A.; Staszak, M. A. *Org. Process Res. Dev.* **2009**, *13*, 1199.
11. (a) Devulapelli, V. G.; Weng, H. S. *Catal. Commun.* **2009**, *10*, 1711; (b) Kirumakki, S. R.; Nagaraju, N.; Narayanan, S. *Appl. Catal. A* **2002**, *226*, 175; (c) Kirumakki, S. R.; Nagaraju, N.; Chary, K. V. R.; Narayanan, S. *Appl. Catal. A* **2003**, *248*, 161.
12. Glasnov, T. N.; Holbrey, J. D.; Kappe, C. O.; Seddon, K. R.; Yan, T. *Green Chem.* **2012**, *14*, 3071.
13. (a) Giordanengo, R.; Viel, S.; Hidalgo, M.; Allard-Breton, B.; Thevand, A.; Charles, L. *Rapid Commun. Mass. Spectrom.* **2010**, *24*, 1941; (b) Otera, J. Wiley-VCH: Weinheim, 2003, 249. (c) Rajapaksa, N. S.; McGowan, M. A.; Rienzo, M.; Jacobsen, E. N. *Org. Lett.* **2013**, *15*, 706; (d) Schrader, T. O.; Johnson, B. R.; Lopez, L.; Kasem, M.; Gharbaoui, T.; Sengupta, D.; Buzard, D.; Basmadjian, C.; Jones, R. M. *Org. Lett.* **2012**, *14*, 6306.
14. (a) Shieh, W.-C.; Dell, S.; Repič, O. *J. Org. Chem.* **2002**, *67*, 2188; (b) Carafa, M.; Mesto, E.; Quaranta, E. *Eur. J. Org. Chem.* **2011**, 2458; (c) Shieh, W.-C.; Dell, S.; Repič, O. *Org. Lett.* **2001**, *3*, 4279.
15. (a) Shieh, W.-C.; Dell, S.; Repič, O. *Tetrahedron Lett.* **2002**, *43*, 5607; (b) Chau, K. D. N.; Duus, F.; Le, T. N. *Green Chem. Lett. Rev.* **2013**, *6*, 89; (c) Caretto, A.; Perosa,

A. *ACS Sustain. Chem. Eng.* **2013**, *1*, 989; (d) Guerrero, L. R.; Rivero, I. R. *ARKIVOC* **2008**, *11*, 295; (e) Gharat, N.; Rathod, V. K. *J. Mol. Catal. B* **2013**, *88*, 36.
16. (a) Dhakshinamoorthy, A.; Sharmila, A.; Pitchumani, K. *Chem.—Eur. J.* **2010**, *16*, 1128; (b) Selva, M.; Tundo, P. *J. Org. Chem.* **2006**, *71*, 1464.
17. (a) Su, X.; Li, J.; Xiao, F.; Wei, W.; Sun, Y. *Ind. Eng. Chem. Res.* **2009**, *43*, 3685; (b) Selva, M.; Tundo, P. *Tetrahedron Lett.* **2003**, *44*, 8139.
18. Ji, Y.; Sweeney, J.; Zoglio, J.; Gorin, D. J. *J. Org. Chem.* **2013**, *78*, 11606.
19. (a) Yang, H.-L.; Sun, P.; Zhu, Y.; Yan, H.; Mao, J.-C. *Chem. Commun.* **2012**, 7847; (b) Yang, H.-L.; Yan, H.; Sun, P.; Zhu, Y.; Mao, J.-C. *Green Chem.* **2013**, *15*, 976; (c) Yan, H.; Lu, L.-H.; Rong, G.-W.; Liu, D.-F.; Mao, J.-C. *J. Org. Chem.* **2014**, *79*, 7103; (d) Rong, G.-W.; Liu, D.-F.; Lu, L.-H.; Yan, H.; Mao, J.-C. *Tetrahedron* **2014**, *70*, 5033.
20. Zhu, Y.; Yan, H.; Lu, L.-H.; Liu, D.-F.; Mao, J.-C. *J. Org. Chem.* **2013**, *78*, 9898.

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