CuI/L-Proline-Catalyzed Coupling Reactions of Vinyl Bromides with Activated Methylene Compounds

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Received 6 March 2006

Abstract: The Ullmann-type coupling reaction of vinyl bromides and activated methylene compounds under CuI/L-proline in DMSO, at 90 °C in the presence of Cs_2CO_3 gives the corresponding vinyl compounds in moderate to good yields. This is a good method for preparing compounds with multiple functional groups including double bonds, carbonyls, and/or esters.

Key words: carbon–carbon coupling reaction, Ullmann-type reaction, activated methylene compounds, copper iodide, vinyl bromide

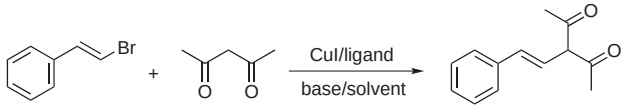
Carbon–carbon bond-forming reactions are among the most important types of bond constructions in organic chemistry.[1] Among many methods available for carbon–carbon bond-forming reactions, a great deal of effort has been focused on the development of palladium-catalyzed methods.[1i,2] Although some exciting achievements have already appeared, high costs and toxicity of Pd reagents limit their application in industry. The Ullmann-type coupling reaction is the most common method for forming a carbon–carbon bond with copper as the catalyst instead of Pd.[3]

The Hurtley reaction is a carbon–carbon coupling reaction of activated methylene compounds in the presence of copper or copper salts. The scope of this type of reaction is very limited, with only *o*-bromobenzoic acid and its closely related bromides being reactive.[4] The major drawback of this reaction is that in nearly all cases stoichiometric or even excess amounts of copper salts must be used to ensure good results.[5] Great progress was made in 1993, when Miura and co-workers reported a coupling reaction using a catalytic amount of copper salts at 120 °C.[6] Today, there are still several laboratories doing research on mild Ullmann-type reactions based on employing specific ligands. Ma's group found that L-proline and other amino acids were effective ligands for copper-catalyzed coupling reactions of aryl halides with amines, *N*-heterocycles, sodium azide, sulfinic acid salts, phenols and 1-alkynes.[3e,7] Buchwald and co-workers also reported various copper-catalyzed coupling reactions.[3d,8]

More recently, Ma and co-workers described the coupling reaction of aryl bromides with activated methylene compounds under CuI/L-proline catalysis.[7j] Bao's group reported the L-proline-promoted Ullmann-type reaction of vinyl bromides with imidazoles in ionic liquids.[9] There are also some papers regarding the reactions of vinyl bromides with phenols and aliphatic alcohols.[7a,10] To the best of our knowledge, efficient procedures for the direct formation of carbon–carbon bonds via condensation of vinyl halides with carbanions in the presence of a catalytic amount of copper or copper salts are relatively scarce. Here, we wish to report the coupling reaction of vinyl bromides with activated methylene compounds.

In order to optimize the coupling reaction conditions, including ligands, bases, solvents, and temperature, the reaction of pentane-2,4-dione was conducted under various conditions, and the results are listed in Table 1.

Table 1 Coupling Reaction of (*E*)-1-(2-bromovinyl)benzene with Pentane-2,4-dione under CuI Catalysis[a]



Entry	Base	Solvent	Ligand	Temp (°C)	Time (h)	Yield (%)[b]
1	Cs_2CO_3	DMSO	L-Proline	90	26	74
2	Cs_2CO_3	DMSO	None	90	20	33
3	Cs_2CO_3	DMSO	Glycine	90	20	30
4	K_2CO_3	DMSO	L-Proline	90	20	18
5	$Na_3PO_4 \cdot 10H_2O$	DMSO	L-Proline	90	20	10
6	Cs_2CO_3	DMF	L-Proline	90	24	20
7	Cs_2CO_3	*p*-xylene	L-Proline	90	20	trace
8	Cs_2CO_3	$[Emim]^+[BF_4]^-$	L-Proline	90	24	0
9	Cs_2CO_3	$[Bmim]^+[BF_4]^-$	L-Proline	90	24	0
10	Cs_2CO_3	$[Bmim]^+[PF_6]^-$	L-Proline	90	24	0
11	Cs_2CO_3	DMSO	L-Proline	35	60	trace
12	Cs_2CO_3	DMSO	L-Proline	120	10	60

[a] Reaction conditions: CuI (0.05 mmol), amino acid (0.1 mmol), (*E*)-1-(2-bromovinyl)benzene (0.5 mmol), base (1 mmol), solvent (2.0 g), N_2 atmosphere.
[b] Isolated yield.

SYNLETT 2006, No. 11, pp 1719–1723
Advanced online publication: 04.07.2006
DOI: 10.1055/s-2006-944227; Art ID: W05006ST
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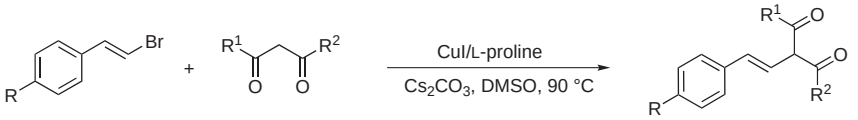
It was found that 10 mol% CuI and 20 mol% L-proline gave (*E*)-3-styrylpentane-2,4-dione in 74% isolated yield (Table 1, entry 1). In the absence of L-proline, the reaction gave only a 33% yield at the same temperature (Table 1, entry 2), whereas glycine proved to be even worse (Table 1, entry 3). L-Proline, therefore, was crucial to this type of coupling reaction. Other bases such as K_2CO_3 or Na_3PO_4 gave the desired product at 90 °C, in poor 18% and 10% yields, respectively (Table 1, entries 4 and 5). Among the solvents examined, the reaction in DMF gave a 20% yield (Table 1, entry 6), while *p*-xylene provided only a trace amount of product (Table 1, entry 7). To our surprise, when this reaction was performed in ionic liquids 1-ethyl-3-methylimidazolium tetrafluoroborate $[emim]^+[BF_4]^-$, 1-butyl-3-methylimidazolium tetrafluoroborate $[bmim]^+[BF_4]^-$ and 1-butyl-3-methylimidazolium hexafluorophosphate $[bmim]^+[PF_6]^-$, no product was detected (Table 1, entries 8–10); we repeated the reaction several times to verify this. By prolonging the reaction time to 60 hours at 35 °C, a trace amount of product was formed (Table 1, entry 11), which indicated that a higher temperature is necessary for the reaction to succeed. The reaction rate increased greatly at elevated temperature (120 °C), but the yield was moderate (Table 1, entry 12), because the product easily decomposed under these conditions. Interestingly, a little of water does not influence the results of the reaction greatly.

Under the optimized reaction conditions, a brief study of the generality of the reaction was undertaken with various vinyl bromides and activated methylene compounds;[11] the results are summarized in Table 2. It seems that the vinylbromide with an electron-withdrawing group (chloro) on the phenyl ring gave the best results when coupled with pentane-2,4-dione, ethyl acetoacetate, and diethyl malonate (Table 2, entries 5–7). However, the electron-donating groups such as methyl or methoxy group on the phenyl rings retarded the reaction and afforded lower yields (Table 2, entries 8–11). This trend is in agreement with the classical Ullmann-type coupling reaction. Notably, some functional vinyl bromides (e.g., chloro, methyl, and methoxy) tolerated the reaction conditions. No desired coupling product was formed from the reaction with (*E*)-1-(2-bromovinyl)-4-methoxybenzene with diethyl malonate (Table 2, entry 12). (*E*)-1-(2-Bromoprop-1-enyl)benzene with some steric hindrance could couple with pentane-2,4-dione and gave the corresponding product in 60% yield (Table 2, entry 13). We found that *Z*-vinyl bromide did not react with 2,4-dione, probably because of the increased steric hindrance (Table 2, entry 14).[9] Of the four activated methylene compounds tested, diethyl malonate presented the best reactivity, maybe due to its lowest acidity.[7j] We obtained none of the desired coupling product when (*E*)-1-(2-bromovinyl)benzene reacted with ethyl cyanoacetate (Table 2, entry 4). The reason for this drawback is not clear yet.

Table 2 Coupling Reaction of Vinyl Bromide with Activated Methylene Compounds under CuI/L-Proline Catalysis[a]



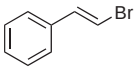
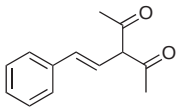
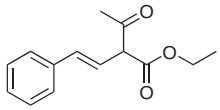
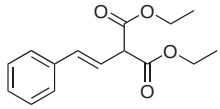
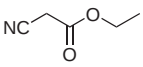
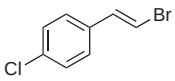
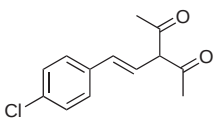
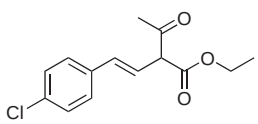
Entry	Vinyl bromide	R^1	R^2	Product	Time (h)	Yield (%)[b]
1		Me	Me		26	74
2		Me	EtO		22	76
3		EtO	EtO		19	80
4				No reaction	20	0
5		Me	Me		26	79
6		Me	EtO		23	81

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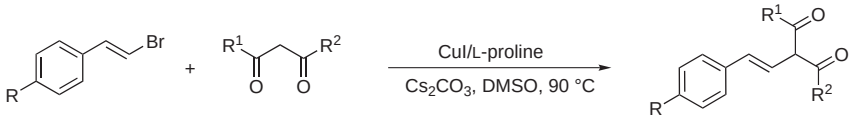
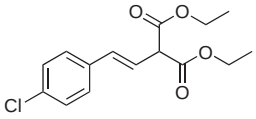
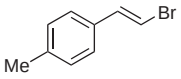
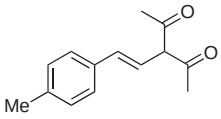
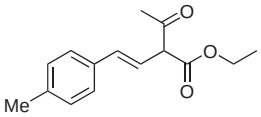
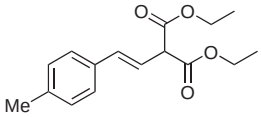
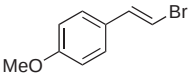
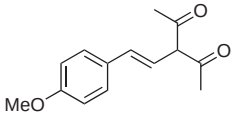
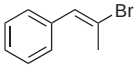
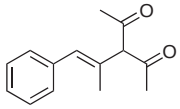
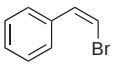
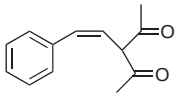
Table 2 Coupling Reaction of Vinyl Bromide with Activated Methylene Compounds under CuI/L-Proline Catalysis[a] (continued)



Entry	Vinyl bromide	R^1	R^2	Product	Time (h)	Yield (%)[b]
7		EtO	EtO		19	84
8		Me	Me		23	70
9		Me	EtO		23	73
10		EtO	EtO		20	77
11		Me	Me		23	50
12		EtO	EtO	No reaction	21	0
13		Me	Me		28	60
14		Me	Me		19	trace

[a] Reaction conditions: CuI (0.05 mmol), L-proline (0.1 mmol), vinyl bromides (0.5 mmol), Cs_2CO_3 (1 mmol), DMSO (2.0 g), N_2 atmosphere.
[b] Isolated yield.

In conclusion, we have developed a new CuI/L-proline-catalyzed coupling reaction of vinyl bromides with activated methylene compounds. The yields of these reactions are moderate to good. The products obtained by this method bear a variety of functional groups and are very useful synthetic intermediates, which can be applied to further reactions. Other CuI/L-proline-catalyzed coupling reactions of vinyl bromides is underway in our laboratory.

Acknowledgment

We are grateful to the Natural Science Foundation of China for financial support (No. 20572095).

References and Notes

(1) (a) Lorsbach, B. A.; Kurth, M. J. *Chem. Rev.* **1999**, *99*, 1549. (b) Sammelson, R. E.; Kurth, M. J. *Chem. Rev.* **2000**, *101*, 137. (c) Dilman, A. D.; Ioffe, S. L. *Chem. Rev.* **2003**, *103*, 733. (d) Casiraghi, G.; Zanardi, F.; Appendino, G.; Rassu, G. *Chem. Rev.* **2000**, *100*, 1929. (e) Luh, T.-Y.; Leung, M.-K.; Wong, K.-T. *Chem. Rev.* **2000**, *100*, 3187. (f) Li, C.-J. *Chem. Rev.* **2005**, *105*, 3095. (g) Fagnou, K.; Lautens, M. *Chem. Rev.* **2003**, *103*, 169. (h) Svedendahl, M.; Hult, K.; Berglund, P. *J. Am. Chem. Soc.* **2005**, *127*, 17988. (i) Fillion, E.; Carson, R. J.; Trépanier, V. E.; Goll, J. M.; Remorova, A. A. *J. Am. Chem. Soc.* **2004**, *126*, 15354.

(2) (a) Jørgensen, M.; Lee, S.; Liu, X.; Wolkowski, J. P.; Hartwig, J. F. *J. Am. Chem. Soc.* **2002**, *124*, 12557. (b) You, J.; Verkade, J. G. *Angew. Chem. Int. Ed.* **2003**, *42*, 5051. (c) You, J.; Verkade, J. G. *J. Org. Chem.* **2003**, *68*, 8003. (d) Beare, N. A.; Hartwig, J. F. *J. Org. Chem.* **2002**, *67*, 541. (e) Stauffer, S. R.; Beare, N. A.; Stambuli, J. P.; Hartwig, J. F. *J. Am. Chem. Soc.* **2001**, *123*, 4641. (f) Fox, J. M.; Huang, X.; Chieffi, A.; Buchwald, S. L. *J. Am. Chem. Soc.* **2000**, *122*, 1360. (g) Moradi, W. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **2001**, *123*, 7996. (h) Terao, Y.; Fukuoka, Y.; Satoh, T.; Miura, M.; Nomura, M. *Tetrahedron Lett.* **2002**, *43*, 101. (i) Lloyd-Jones, G. C. *Angew. Chem. Int. Ed.* **2002**, *41*, 953. (j) Kashin, A. N.; Mitin, A. V.; Beletskaya, I.

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P.; Wife, R. *Tetrahedron Lett.* **2002**, *43*, 2539. (k) Hamada, T.; Chieffi, A.; Åhman, J.; Buchwald, S. L. *J. Am. Chem. Soc.* **2002**, *124*, 1261. (l) Viciu, M. S.; Germaneau, R. F.; Nolan, S. P. *Org. Lett.* **2002**, *4*, 4053.

(3) (a) Hassan, J.; Sévignon, M.; Gozzi, C.; Schulz, E.; Lemaire, M. *Chem. Rev.* **2002**, *102*, 1359. (b) Ley, S. V.; Thomas, A. W. *Angew. Chem. Int. Ed.* **2003**, *42*, 5400. (c) Kunz, K.; Scholz, U.; Ganzer, D. *Synlett* **2003**, 2428. (d) Hennessy, E. J.; Buchwald, S. L. *Org. Lett.* **2002**, *4*, 269. (e) Ma, D.; Liu, F. *Chem. Commun.* **2004**, 1934. (f) Zhang, S.; Zhang, D.; Liebeskind, L. S. *J. Org. Chem.* **1997**, *62*, 2312. (g) Bates, C. G.; Saejueng, P.; Venkataraman, D. *Org. Lett.* **2004**, *6*, 1441. (h) Jiang, Y.; Wu, N.; Wu, H.; He, M. *Synlett* **2005**, 2731.

(4) (a) Hurtley, W. R. H. *J. Chem. Soc.* **1929**, 1870. (b) Bruggink, A.; Ray, S. J.; McKillop, A. *Org. Synth.* **1978**, *58*, 52. (c) Bryson, T. A.; Stewart, J. J.; Gibson, J. M.; Thomas, P. S.; Berch, J. K. *Green Chem.* **2003**, *5*, 174. (d) Bruggink, A.; McKillop, A. *Tetrahedron* **1975**, *31*, 2607. (e) Lindley, J. *Tetrahedron* **1984**, *40*, 1433. (f) Shinkwin, A. E.; Whish, W. J. D.; Threadgill, M. D. *Bioorg. Med. Chem.* **1999**, *7*, 297.

(5) (a) Hang, H. C.; Drotleff, E.; Elliott, G. I.; Ritsema, T. A.; Konopelski, J. P. *Synthesis* **1999**, 398. (b) Suzuki, H.; Yi, Q.; Inoue, J.; Kusume, K.; Ogawa, T. *Chem. Lett.* **1987**, 887. (c) Suzuki, H.; Kobayashi, T.; Osuka, A. *Chem. Lett.* **1983**, 589.

(6) Okuro, K.; Furuune, M.; Miura, M.; Nomura, M. *J. Org. Chem.* **1993**, *58*, 7606.

(7) (a) Ma, D.; Cai, Q.; Xie, X. *Synlett* **2005**, 1767. (b) Zhu, W.; Ma, D. *J. Org. Chem.* **2005**, *70*, 2696. (c) Cai, Q.; Zhu, W.; Zhang, H.; Zhang, Y.; Ma, D. *Synthesis* **2005**, 496. (d) Ma, D.; Cai, Q.; Zhang, H. *Org. Lett.* **2003**, *5*, 2453. (e) Ma, D.; Cai, Q. *Org. Lett.* **2003**, *5*, 3799. (f) Ma, D.; Cai, Q. *Synlett* **2004**, 128. (g) Pan, X.; Cai, Q.; Ma, D. *Org. Lett.* **2004**, *6*, 1809. (h) Zhu, W.; Ma, D. *Chem. Commun.* **2004**, 888. (i) Zhang, H.; Cai, Q.; Ma, D. *J. Org. Chem.* **2005**, *70*, 5164. (j) Xie, X.; Cai, G.; Ma, D. *Org. Lett.* **2005**, *7*, 4693.

(8) (a) Marcoux, J.-F.; Doye, S.; Buchwald, S. L. *J. Am. Chem. Soc.* **1997**, *119*, 10539. (b) Kiyomori, A.; Marcoux, J. F.; Buchwald, S. L. *Tetrahedron Lett.* **1999**, *40*, 2657. (c) Wolter, M.; Klapars, A.; Buchwald, S. L. *Org. Lett.* **2001**, *3*, 3803. (d) Klapars, A.; Antilla, J. C.; Huang, X.; Buchwald, S. L. *J. Am. Chem. Soc.* **2001**, *123*, 7727. (e) Antilla, J. C.; Buchwald, S. L. *Org. Lett.* **2001**, *3*, 2077.

(9) Wang, Z.; Bao, W.; Jiang, Y. *Chem. Commun.* **2005**, 2849.

(10) (a) Wan, Z.; Jones, C. D.; Koenig, T. M.; Pu, Y. J.; Mitchell, D. *Tetrahedron Lett.* **2003**, *44*, 8257. (b) Willis, M. C.; Taylor, D.; Gillmore, A. T. *Chem. Commun.* **2003**, 2222. (c) Nordmann, G.; Buchwald, S. L. *J. Am. Chem. Soc.* **2003**, *125*, 4978.

(11) **Typical Procedure:** A two-necked flask was charged with vinyl bromide (0.5 mmol), CuI (0.05 mmol), L-proline (0.1 mmol), and Cs_2CO_3 (1.0 mmol), evacuated, and backfilled with nitrogen. The activated methylene compound (1.0 mmol) and DMSO (2 g) were added under nitrogen. The flask was immersed in a pre-heated oil bath, and the reaction mixture was stirred at 90 °C until the conversion was complete (detected by TLC). The cooled mixture was purified by column chromatography on silica gel (PE–EtOAc, 10:1 to 5:1) to provide the desired product.
(*E*)-3-Styrylpentane-2,4-dione (Table 2, entry 1): IR (film): 3429.1, 3062.4, 3029.7, 2927.2, 1709.1, 1600.9, 1495.2, 1450.2, 1357.4, 1204.9, 1143.7, 1025.8, 976.2, 751.0, 699.4 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.21 (6 H, s, CH_3), 6.41 (1 H, d, *J* = 16.4 Hz, CH), 6.74 (1 H, d, *J* = 16.4 Hz, CH), 7.34–7.43 (5 H, m, ArH) 16.75 (1 H, s, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 24.23, 111.30, 122.73, 126.05, 127.65, 128.66, 134.16, 137.02, 191.16. MS (70 eV): *m*/*z* (%) = 209.0992 (43), 176.0828 (100). HRMS (70 eV): *m*/*z* calcd for $C_{13}H_{14}O_2$, 202.0988; found: 202.0992.
(*E*)-Ethyl-2-acetyl-4-phenylbut-3-enoate (Table 2, entry 2): IR (film): 3459.6, 3061.9, 3029.3, 2982.8, 2936.7, 1732.5, 1599.7, 1449.9, 1368.5, 1247.5, 1079.8, 1018.0, 757.9, 699.6 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.29 (1.2 H, t, *J* = 7.2 Hz, CH_3), 1.35 (1.8 H, t, *J* = 7.2 Hz, CH_3), 2.22 (1.8 H, s, CH_3), 2.28 (1.2 H, s, CH_3), 4.23 (0.8 H, q, *J* = 7.2 Hz, CH_2), 4.24 (0.4 H, s, CH), 4.30 (1.2 H, q, *J* = 7.2 Hz, CH_2), 6.42 (0.4 H, dd, *J* = 16.0, 9.2 Hz, CH), 6.58 (0.4 H, d, *J* = 16.0 Hz, CH), 6.60 (0.6 H, d, *J* = 16.0 Hz, CH), 6.74 (0.6 H, d, *J* = 16.0 Hz, CH), 7.31–7.42 (5 H, m, ArH), 13.37 (0.6 H, s, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 14.03, 14.19, 20.28, 28.45, 60.92, 61.68, 63.87, 101.28, 120.99, 121.57, 125.91, 126.56, 127.04, 128.18, 128.54, 128.60, 130.62, 135.36, 135.99, 138.03, 168.41, 172.63, 174.64, 201.38. MS (70 eV): *m*/*z* (%) = 232.1099 (84) [M^+], 205.0856 (100), 190.0986 (97), 171.0440 (62). HRMS (70 eV): *m*/*z* calcd for $C_{14}H_{16}O_3$: 232.1094; found: 232.1099.
(*E*)-Diethyl-2-styrylmalonate (Table 2, entry 3): IR (film): 2983.3, 2938.7, 2909.6, 1732.6, 1465.2, 1449.4, 1369.3, 1258.4, 1151.3, 1033.8, 967.1, 857.8, 757.9, 692.7 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.28 (6 H, t, *J* = 7.2 Hz, CH_3), 4.17–4.26 (5 H, m, CH_2, CH), 6.42 (1 H, dd, *J* = 16.0, 8.8 Hz, CH), 6.59 (1 H, d, *J* = 16.0 Hz, CH), 7.27–7.42 (5 H, m, ArH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 13.96, 55.86, 61.40, 120.84, 126.56, 128.01, 128.49, 134.96, 136.04, 167.96. MS (70 eV): *m*/*z* (%) = 262.1204 (100) [M^+], 190.0989 (53), 189.0911 (28). HRMS (70 eV): *m*/*z* calcd for $C_{15}H_{18}O_4$: 262.1200; found: 262.1204.
(*E*)-3-(4-Chlorostyryl)pentane-2,4-dione (Table 2, entry 5): IR (film): 3055.4, 2913.6, 1443.6, 1071.7, 748.8, 692.1 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.22 (6 H, s, CH_3), 6.36 (1 H, d, *J* = 16.4 Hz, CH), 6.72 (1 H, d, *J* = 16.4 Hz, CH), 7.30–7.36 (4 H, m, ArH) 16.78 (1 H, s, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 24.27, 111.12, 123.38, 127.23, 128.78, 132.74, 133.22, 135.51, 191.20. MS: *m*/*z* (%) = 236.0601 (100) [M^+], 238.0575 (35) [M^+ + 2], 221.0365 (30). HRMS (70 eV): *m*/*z* calcd for $C_{13}H_{13}ClO_2$: 236.0599; found: 236.0601.
(*E*)-Ethyl-2-acetyl-4-(4-chlorophenyl)but-3-enoate (Table 2, entry 6): IR (film): 3471.5, 2982.2, 2929.3, 1722.1, 1592.1, 1491.8, 1368.8, 1247.0, 1092.0, 1013.7, 974.4, 828.9 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.30 (1.2 H, t, *J* = 7.2 Hz, CH_3), 1.36 (1.8 H, t, *J* = 7.2 Hz, CH_3), 2.22 (1.8 H, s, CH_3), 2.29 (1.2 H, s, CH_3), 4.24 (0.8 H, q, *J* = 7.2 Hz, CH_2), 4.25 (0.4 H, s, CH), 4.30 (1.2 H, q, *J* = 7.2 Hz, CH_2), 6.40 (0.4 H, dd, *J* = 16.0, 8.8 Hz, CH), 6.52 (0.4 H, d, *J* = 16.0 Hz, CH), 6.56 (0.6 H, d, *J* = 16.0 Hz, CH), 6.71 (0.6 H, d, *J* = 16.0 Hz, CH), 7.27–7.34 (4 H, m, ArH), 13.41 (0.6 H, s, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 14.04, 14.22, 20.32, 28.56, 61.02, 61.81, 63.72, 76.61, 101.10, 121.67, 122.15, 127.06, 127.77, 128.66, 128.79, 129.09, 132.50, 134.07, 134.48, 136.58, 168.27, 172.53, 175.02, 201.13. MS (70 eV): *m*/*z* (%) = 216.1146 (100) [M^+], 268.0679 (38) [M^+ + 2], 240.0554 (40), 224.0598 (80), 220.0288 (74), 207.0022 (42), 205.0052 (98). HRMS (70 eV): *m*/*z* calcd for $C_{14}H_{15}ClO_3$: 266.0704; found: 216.1146.
(*E*)-Diethyl-2-(4-chlorostyryl)malonate (Table 2, entry 7): IR (film): 2983.7, 2934.6, 1732.7, 1492.2, 1465.7, 1446.6, 1369.5, 1256.7, 1151.2, 1094.7, 1035.1, 968.7, 821.9 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 1.29 (6 H, t, *J* = 7.2 Hz, CH_3), 4.16–4.26 (5 H, m, CH_2, CH), 6.40 (1 H, dd, *J* = 16.0, 8.8 Hz, CH), 6.55 (1 H, d, *J* = 16.0 Hz, CH), 7.28–7.35 (4 H,

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m, ArH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 13.89, 55.66, 61.33, 121.49, 127.71, 128.59, 133.65, 134.50, 167.73. MS (70 eV): *m*/*z* (%) = 296.0818 (100) [M^+], 298.0784 (32) [M^+ + 2], 224.0600(80), 223.0522 (35), 178.0181 (40). HRMS (70 eV): *m*/*z* calcd for $C_{15}H_{17}ClO_4$: 296.0810; found: 296.0818.

(*E*)-3-(4-Methylstyryl)pentane-2,4-dione (Table 2, entry 8): IR (film): 3055.4, 2913.6, 1443.6, 1071.7, 748.8, 692.1 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.21 (6 H, s, CH_3), 2.36 (3 H, s, CH_3), 6.38 (1 H, d, *J* = 16.0 Hz, CH), 6.68 (1 H, d, *J* = 16.0 Hz, CH), 7.16 (2 H, d, *J* = 8.0 Hz, ArH), 7.16 (2 H, d, *J* = 8.0 Hz, ArH), 16.71 (1 H, s, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.18, 24.23, 111.40, 121.72, 125.99, 129.36, 134.17, 134.24, 137.61, 191.13. MS (70 eV): *m*/*z* (%) = 216.1148 (100) [M^+], 201.0912 (61). HRMS (70 eV): *m*/*z* calcd for $C_{14}H_{16}O_3$: 216.1145; found: 216.1148.

(*E*)-Ethyl-2-acetyl-4-*p*-tolylbut-3-enoate (Table 2, entry 9): IR (film): 3459.1, 2981.7, 2923.5, 2868.0, 1721.8, 1639.5, 1604.2, 1513.6, 1369.4, 1245.6, 1061.4, 1019.3, 968.6, 860.4, 817.5 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.29 (1.2 H, t, *J* = 7.2 Hz, CH_3), 1.34 (1.8 H, t, *J* = 7.2 Hz, CH_3), 2.21 (1.8 H, s, CH_3), 2.27 (1.2 H, s, CH_3), 2.34 (3 H, s, CH_3), 4.23 (0.8 H, q, *J* = 7.2 Hz, CH_2), 4.24 (0.3 H, s, CH), 4.28 (1.2 H, q, *J* = 7.2 Hz, CH_2), 6.36 (0.4 H, dd, *J* = 16.0, 8.8 Hz, CH), 6.54 (0.4 H, d, *J* = 16.0 Hz, CH), 6.55 (0.6 H, d, *J* = 16.0 Hz, CH), 6.68 (0.6 H, d, *J* = 16.0 Hz, CH), 7.13 (2 H, d, *J* = 8.0 Hz, ArH), 7.29–7.31 (2 H, m, ArH), 13.34 (0.6 H, s, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 14.02, 14.19, 20.23, 21.10, 21.17, 28.38, 60.85, 61.61, 63.91, 101.33, 119.90, 120.58, 125.82, 126.46, 129.22, 129.27, 130.66, 133.24, 135.22, 135.25, 136.85, 138.10, 168.51, 172.67, 174.32, 201.51. MS (70 eV): *m*/*z* (%) = 246.1254 (72) [M^+], 204.1145 (38), 200.0832 (77), 185.0596 (100), 158.0727 (27). HRMS (70 eV): *m*/*z* calcd for $C_{15}H_{18}O_3$: 246.1250; found: 246.1254.

(*E*)-Diethyl-2-(4-methylstyryl)malonate (Table 2, entry 10): IR (film): 2982.2, 2937.9, 1732.6, 1513.8, 1463.9, 1446.3, 1368.5, 1293.0, 1257.3, 1177.2, 1096.2, 1032.1, 968.5, 862.0, 812.0 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.28 (6 H, t, *J* = 7.2 Hz, CH_3), 2.33 (3 H, s, CH_3), 4.16 (1 H, d, *J* = 9.2 Hz, CH), 4.23 (4 H, q, *J* = 7.2 Hz, CH_2), 6.42 (1 H, dd, *J* = 16.0, 9.2 Hz, CH), 6.55 (1 H, d, *J* = 16.0 Hz, CH), 7.13 (2 H, d, *J* = 8.0 Hz, ArH), 7.31 (2 H, d, *J* = 8.0 Hz, ArH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 14.01, 21.19, 55.94, 61.73, 119.79, 126.50, 129.22, 133.31, 134.89, 137.95, 168.12. MS (70 eV): *m*/*z* (%) =(100) [M^+], 204.1147 (26), 203.1071 (28), 157.0647 (21), 129.0698 (51). HRMS (70 eV): *m*/*z* calcd for $C_{16}H_{20}O_4$: 276.1356; found: 276.1363.

(*E*)-3-(4-Methoxystyryl)pentane-2,4-dione (Table 2, entry 11): IR (film): 3055.4, 2913.6, 1443.6, 1071.7, 748.8, 692.1 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.21 (6 H, s, CH_3), 2.96 (3 H, s, CH_3), 6.35 (1 H, d, *J* = 16.0 Hz, CH), 6.59 (1 H, d, *J* = 16.0 Hz, CH), 6.89–6.91 (2 H, m, ArH), 7.35–7.37 (2 H, m, ArH), 16.68 (1 H, s, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 24.24, 55.34, 111.47, 114.14, 120.57, 127.29, 130.23, 133.88, 140.17, 191.10. MS (70 eV): *m*/*z* (%) = 232.1099 (100) [M^+], 204.0782 (63), 133.0648 (37). HRMS (70 eV): *m*/*z* calcd for $C_{14}H_{16}O_3$: 232.1094; found: 232.1099.

(*E*)-3-(1-Phenylprop-1-en-2-yl)pentane-2,4-dione (Table 2, entry 13): IR (film): 3055.4, 2913.6, 1443.6, 1071.7, 748.8, 692.1 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 1.99 (2 H, s, CH_3), 2.05 (3 H, d, *J* = 1.2 Hz, CH_3), 2.13 (4 H, s, CH_3), 6.42 (0.65 H, s, CH), 6.52 (0.35 H, s, CH), 7.18–7.40 (5 H, m, ArH), 16.40 (0.65 H, s, OH), 16.50 (0.35 H, s, OH). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 20.31, 22.84, 23.17, 27.05, 113.13, 118.18, 126.83, 126.92, 127.73, 128.25, 128.45, 128.64, 131.01, 132.60, 133.04, 133.46, 137.03, 137.34, 189.87, 190.14. MS (70 eV): *m*/*z* (%) = 216.1146 (100) [M^+], 201.0912 (87), 173.0961 (25). HRMS (70 eV): *m*/*z* calcd for $C_{14}H_{16}O_2$: 216.1145; found: 216.1146.

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