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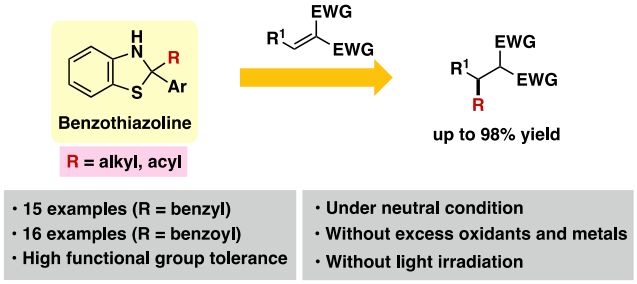
Supporting Information Placeholder



ABSTRACT: The hydroalkylation and hydroacylation of electron-deficient alkenes proceeded smoothly by using benzothiazoline derivatives as the radical transfer reagent under thermal conditions without light irradiation or any additive. Both benzyl and benzoyl moieties were transferred efficiently.

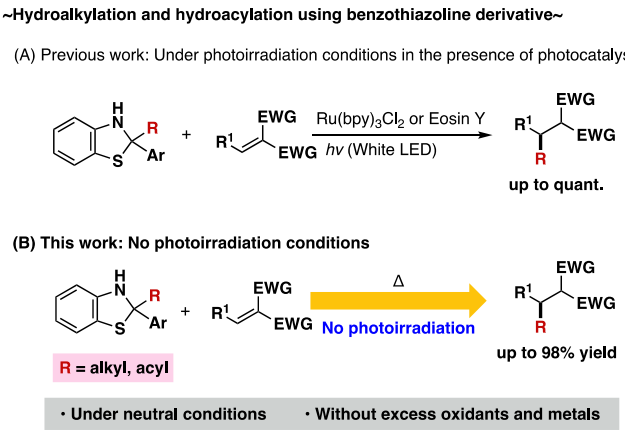
1. INTRODUCTION

The alkyl or acyl radical transfer to C–C double bonds has attracted much attention because this reaction takes place under mild conditions and has high functional group tolerance.[1,2] Stoichiometric amounts of expensive or toxic materials are generally required to generate radical species.[3] Photoinduced alkyl and acyl radical generation reactions that use photoredox catalysts were reported recently.[4,5] However, some photoredox catalysts are expensive, and large scale reaction is not always a trivial issue. In order to address these issues, the development of alkyl and acyl radical transfer reagents that function under transition-metal- and light-free conditions is desired. Although Hantzsch ester was found to function as a metal- and light-free alkyl transfer reagent for imines and electron-deficient alkenes,[6] acidic conditions or radical initiators were necessary.

We found that benzothiazoline derivatives functioned as alkyl and acyl radical transfer reagents in combination with photoredox catalysts, and reported visible light induced hydroalkylation and hydroacylation of alkenes (Scheme 1A).[7–9] In that study, we found that the alkyl radical transfer reaction slightly proceeded under dark conditions (24%, 24 h). This finding prompted us to study the hydroalkylation and hydroacylation reactions of alkenes under thermal conditions without any catalysts.

We wish to disclose herein the hydroalkylation and hydroacylation of alkenes by using benzothiazoline derivatives under thermal conditions without transition metals or light irradiation (Scheme 1B).

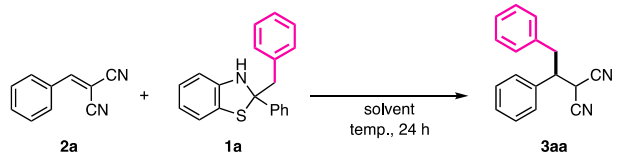
Scheme 1. Hydroalkylation and hydroacylation using benzothiazoline derivatives.



2. RESULTS AND DISCUSSIONS

First, an alkyl transfer reaction with radical acceptors was investigated by using benzothiazolines bearing a 2-benzyl moiety. When a 50 mM 1,2-dichloroethane solution of benzalmalononitrile (**2a**) was treated with 2-benzyl-2-phenylbenzothiazoline (**1a**) at 60 °C, desired alkylation product **3aa** was obtained in 27% yield (Table 1, entry 1). Use of ethanol as the solvent improved the yield of **3aa** to 76% (entry 3). Interestingly, when the reaction temperature was increased to 80 °C, the yield dropped to 44% (entry 4). The highest yield (89%) was obtained when 2-propanol was used at 80 °C (entry 5).

Table 1. Screening for hydrobenzylation conditions [a)]

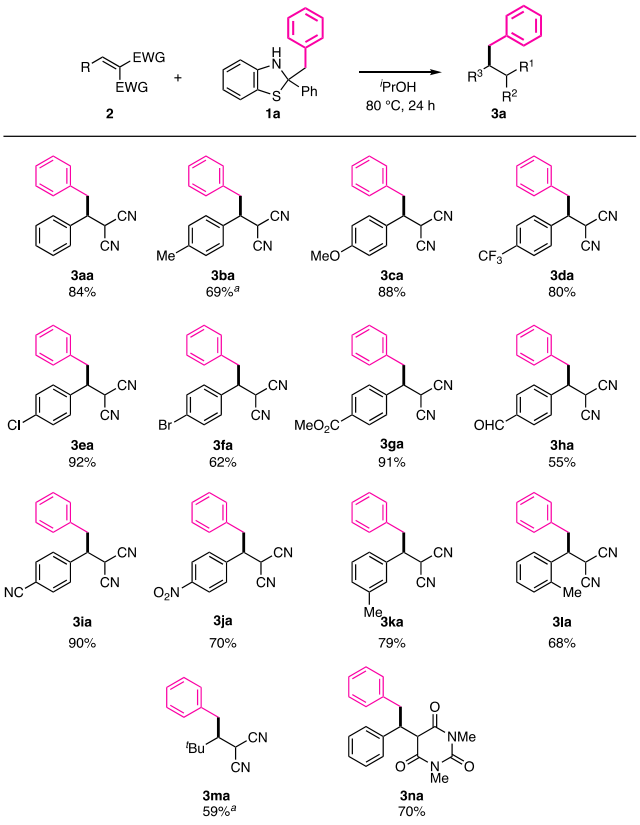


2a 1a 3aa

Entry	Solvent	Temp.	Yield[b)]
1	DCE	60 °C	27%
2	DMF	60 °C	10%
3	EtOH	60 °C	76%
4	EtOH	80 °C	44%
5[c)]	^{i}PrOH	80 °C	89%

(a) Performed with **2a** (0.050 mmol) and **1a** (0.10 mmol) in solvent (1.0 mL). (b) Determined by ^{1}H NMR (1,1,2-trichloroethane was used as the internal standard). (c) Using non-degassed solvent. DCE: 1,2-dichloroethane, DMF: *N*,*N*-dimethylformamide.

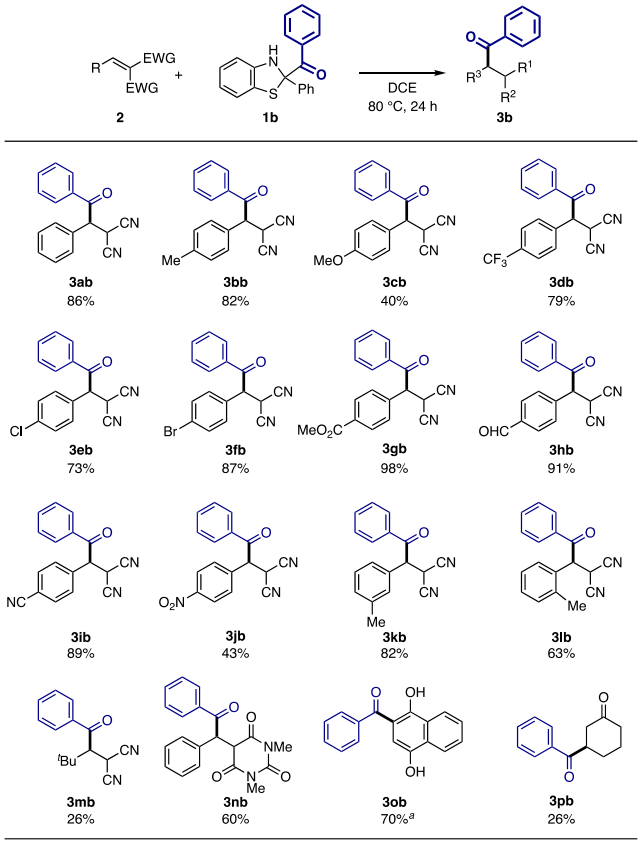
Under the optimized conditions, we investigated the substrate scope of the alkyl transfer reactions (Figure 1). Several *para*-substituted benzalmalononitrile derivatives could be applied to this reaction. Substrates bearing electron-donating groups (**2b**, –Me; **2c**, –OMe) and electron-withdrawing groups (**2d**, –CF_3; **2e**, **2f**, halogen; **2g**, –CO_2Me; **2i**, –CN; **2j**, –NO_2) gave the products in moderate to high yields. It is noted that the formyl group was compatible to furnish desired hydroalkylation product **3ha** in moderate yield. This selectivity suggests a radical pathway rather than an ionic one. *Meta*- and *ortho*-substituted benzalmalononitrile were also suitable substrates to furnish the products in high yields (**2k**, **2l**). Furthermore, alkylidene malononitrile **2m** could also be applied to afford corresponding adduct **3ma** in 59% yield. Other types of electron-deficient alkenes were also applicable. Barbituric acid derivative **2n** reacted efficiently.



[a] The reaction was carried out for 48 h. [b] NMR yield.

Figure 1. Substrate scope of hydrobenzylation.

An acyl transfer reaction could also be applied to this system. Treatment of 2-benzyl-2-phenylbenzothiazoline (**1b**) with **2a** in DCE at 80 °C furnished hydrobenzoylation product **3ab** quantitatively (Table S2, see Supporting Information). The substrate scope of the hydrobenzoylation reaction is shown in Figure 2. Malononitrile derivatives underwent hydrobenzoylation with reasonable functional group tolerance. Barbituric acid **2n** and naphthoquinone **2o** also reacted to give adducts in good yields. Furthermore, simple enone **2p**, which could not undergo hydroalkylation, gave adduct **3pb** in moderate yield.



[a] NMR yield.

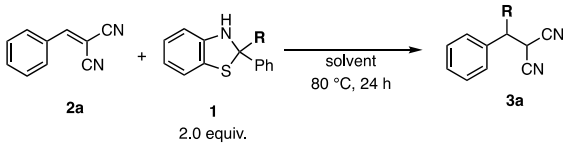
Figure 2. Substrate scope of hydrobenzoylation.

Next, the scope of the transferred alkyl and acyl groups was investigated (Table 2). A *p*-substituted benzyl group was transferred efficiently to give adduct **3ac** in good yield. A *tert*-butyl group could be transferred efficiently to afford **3ad** in 91% yield. It is noted that an isopropyl group, which was not transferred under the photoredox conditions, also underwent the transfer reaction to give **3ae** albeit in modest yield. Isopropyl group was not transferred under the photoredox conditions probably because heating was necessary for C–C bond cleavage in **1e**.[7]

The diethoxymethyl group as a formyl equivalent could also be transferred and product **3af** was obtained quantitatively.[10] Benzoyl derivatives bearing electron-rich (**3ag**) and electron-deficient (**3ah**) substituents were transferred efficiently in DCE to furnish the adducts in good yields. Furthermore, the acetyl moiety was also transferred to give **3ai** in 88% yield. On the other hand, a pivaloyl group could not be transferred because it underwent decarbonylation into a *tert*-butyl radical, and *tert*-butyl adduct **3ad** was obtained in 79% yield.

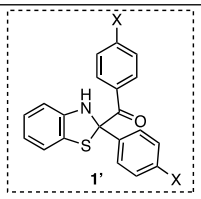
Overall, present radical hydroalkylation and hydroacylation reaction under thermal conditions exhibited mostly similar reactivity and scope of substrate in comparison with those under photoredox conditions. [7]

Table 2. Generation of alkyl and acyl groups.



R (in ^{i}PrOH)	Me			OEt, OEt
	3ac	**3ad**	**3ae**	**3af**
yield	73%	91%	18%[a]	34%[a]

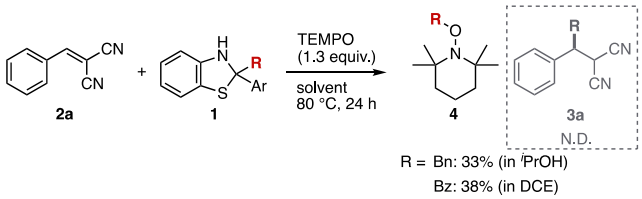
R (in DCE)	Me	Br		^{t}Bu
	3ag	**3ah**	**3ai**	**3aj**
yield	67%[a]	62%[a]	88%	0%[b]



[a] Benzothiazoline **1'** bearing *p*-substituted phenyl group at 2-position was used. [b] *tert*-Butyl adduct **3ad** was obtained in 79% yield.

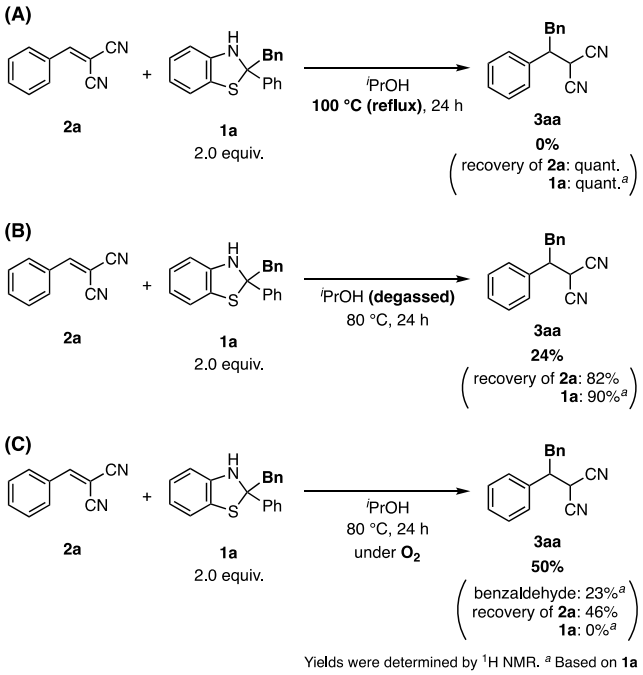
In order to acquire mechanistic insight, a radical scavenging experiment was carried out in the presence of TEMPO. TEMPO adduct **4** was obtained and both hydroalkylation and hydroacylation reactions of **2a** were completely inhibited (Scheme 2). These results support the radical pathway.

Scheme 2. Radical scavenging experiment.



Finally, we take note of the dependence on the reaction temperature. When ethanol was used as the solvent in Table 1, the yield of the product dropped when temperature was increased from 60 °C (76%) to 80 °C (44%). We investigated the details of this phenomenon by performing the reaction under ^{i}PrOH at 100 °C (reflux conditions). Surprisingly, the desired reaction did not proceed at all under these conditions and starting materials **1a** and **2a** were recovered quantitatively (Scheme 3A). We suppose that the decrease of the product yield was caused by solvent degassing under reflux conditions.[11] The hydroalkylation was retarded by using degassed ^{i}PrOH, and starting materials **1a** and **2a** were recovered (Scheme 3B). These results indicate that oxygen was inevitable for this reaction. Performing the reaction under oxygen gave desired product **3aa** in 50% yield accompanied by the recovery of benzalmalononitrile (**2a**) in 46% yield (Scheme 3C). This is in contrast with the complete consumption of benzothiazoline **1a**, and benzaldehyde, generated from benzyl radical with oxygen, was obtained in 23% yield (based on **1a**). Therefore, a small amount of oxygen was inevitable to initiate the reaction by oxidizing benzothiazoline **1**.[12]

Scheme 3. Control experiments



We propose a reaction mechanism as shown in Figure 3. As the initiation of the reaction, benzothiazoline **1** is oxidized by oxygen under heating conditions to generate cation radical species **1**$^{\bullet+}$. Generated cation radical species **1**$^{\bullet+}$ releases radical species (R•) and the radical species adds to substrate **2.** This is followed by a reduction via single-electron-transfer (SET) with benzothiazoline **1** to generate cation radical **1**$^{\bullet+}$.[13] Thus, the reaction proceeds as a radical chain reaction. Finally, the generated carbanion is protonated by **5-H**$^{+}$ or solvent to give product **3**. Under an excess amount of oxygen, the SET with benzothiazoline does not proceed smoothly, and the reaction fails to advance efficiently.

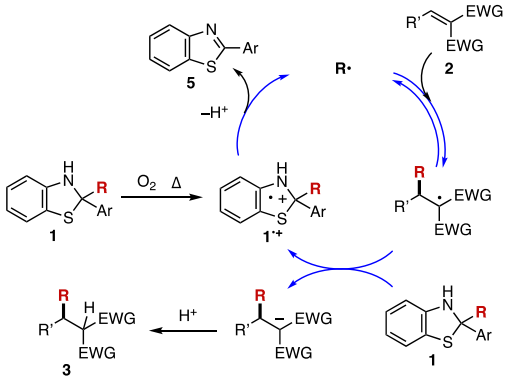


Figure 3. Proposed Mechanism

3. CONCLUSION

In conclusion, we have developed hydroalkylation and hydroacylation reactions of electron-deficient alkenes by using benzothiazoline derivatives as the radical transfer reagent. The use of additives, such as external oxidants, Lewis acids, and transition metals, was obviated. Furthermore, reasonable functional group tolerance was realized and a large-scale reaction was applicable. Thus, this new radical addition using benzothiazoline derivatives is expected to be useful in organic synthesis.

4. EXPERIMENTAL SECTION

4.1. General methods. All operations were performed under air unless otherwise noted. NMR spectra for products data (^{1}H and ^{13}C{^{1}H}) were recorded on a Bruker AVANCE-III (400 MHz for ^{1}H, 100 MHz for ^{13}C{^{1}H}) and JEOL ECZ-400 (400 MHz for ^{1}H, 100 MHz for ^{13}C{^{1}H}) spectrometer using $CDCl_3$ [tetramethylsilane (0 ppm) served as an internal standard in ^{1}H NMR and $CDCl_3$ (77.0 ppm) in ^{13}C{^{1}H} NMR, hexafluorobenzene (−163 ppm) served as an external standard in ^{19}F NMR]. Chemical shifts are expressed in parts per million (ppm). IR spectra were recorded on an FT/IR-4200 (JASCO Co., Ltd.). UV–Vis spectra were recorded on a V-670 UV–VIS–NIR spectrophotometer (JASCO Co., Ltd.). ESI mass analyses were performed on Bruker micrOTOF mass spectrometer. All solvents were distilled according to the usual procedures and stored over molecular sieves unless otherwise noted. All of the substrates were purified by distillation (for liquid) or recrystallization (for solid). Benzalmalononitrile derivatives,[14] malonate derivatives,[15–18] benzothiazolines[7] were synthesized according to the literature procedures. Other chemicals were purchased and used as received.

4.2. General procedure of hydroalkylation (Procedure I). Alkenes (0.05 mmol) and **1a** (30.4 mg, 0.1 mmol) were dissolved in 2-propanol (1.0 mL), and the mixture was warmed at 80 °C (by EYELA Personal Organic Synthesizer Chemistation) for 24 h. The solvent was evaporated and 1,1,2-trichloroethane was added as an internal standard and ^{1}H NMR was measured in $CDCl_3$ for the calculation of the NMR yield. Then crude products were purified by preparative TLC to give **3**. Other hydroalkylation reactions in Figure 1 were performed based on this Procedure I.

*2-(1,2-Diphenylethyl)propanedinitrile (**3aa**)*. Yield 84% (10.3 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45–7.37 (m, 5 H), 7.34–7.27 (m, 3H), 7.21–7.17 (m, 2H), 3.85 (d, J = 4.8 Hz, 1H), 3.50–3.42 (m, 1H), 3.27–3.21 (m, 2H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 136.6, 136.4, 129.23, 129.19, 129.1, 128.9, 128.0, 127.6, 112.1, 111.4, 48.3, 38.5, 28.5 ppm.[19]

*2-[1-(4-Methylphenyl)-2-phenylethyl]propanedinitrile (**3ba**)*. Yield 69% (NMR yield), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.27 (m, 5H), 7.24–7.18 (m, 4H), 3.82 (d, J = 4.8 Hz, 1H), 3.50–3.40 (m, 1H), 3.31–3.18 (m, 2H), 2.37 (s, 3H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 139.0, 136.8, 133.4, 129.9, 129.2, 128.9, 127.8, 127.6, 112.2, 111.5, 48.0, 38.5, 28.7, 21.2 ppm.[7]

*2-[1-(4-Methoxylphenyl)-2-phenylethyl]propanedinitrile (**3ca**)*. Yield 88% (12.2 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.89 (d, J = 8.4 Hz, 2H), 7.55 (t, J = 7.6 Hz, 1H), 7.41 (d, J = 7.6 Hz, 2H), 7.29–7.21 (m, 2H), 6.92 (d, J = 9.2 Hz, 2H), 5.06 (d, J = 8.4 Hz, 1H), 4.50 (d, J = 8.8 Hz, 1H), 3.78 (s, 3H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 193.1, 160.6, 134.3, 133.9, 129.9, 129.3, 128.9, 123.8, 115.5, 112.2, 111.7, 55.3, 54.2, 26.9 ppm; IR (neat, cm^{-1}): 2916, 1682, 1609, 1512, 1258, 1181, 1030, 755, 689; LRMS (ESI): *m/z* = 313 [M+H] HRMS (ESI) Calcd for $C_{18}H_{14}N_2O_2Na$: 313.0947. Found 313.0947.

*2-[1-(4-Trifluoromethylphenyl)-2-phenylethyl]propanedinitrile (**3da**)*. Yield 80% (12.6 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.70 (d, J = 8.0 Hz, 2H), 7.54 (d, J = 8.4 Hz, 2H), 7.39–7.29 (m, 3H), 7.14–7.10 (m, 2H), 3.88 (d, J = 5.2 Hz, 1H), 3.57–3.50 (m, 1H), 3.34–3.21 (m, 2H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 140.2, 135.9, 131.4 (q, $^2J_{C–F}$ = 32 Hz), 129.4, 129.0, 128.9, 128.6, 127.9,126.2 (q, $^3J_{C–F}$ = 3.7 Hz), 123.6 (q, $^1J_{C–F}$ = 271 Hz), 111.2, 111.1,

48.0, 38.3, 28.2 ppm; ^{19}F NMR (376 MHz, $CDCl_3$): δ −64.29 (s, 3F) ppm.[7]

*2-[1-(4-Chlorophenyl)-2-phenylethyl]propanedinitrile **(3ea)***. Yield 92% (12.9 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.87 (d, *J* = 8.4 Hz, 2H), 7.58 (t, *J* = 7.6 Hz, 1H), 7.50–7.35 (m, 4H), 7.35–7.27 (m, 2H), 5.10 (d, *J* = 8.0 Hz, 1H), 4.52 (d, *J* = 8.4 Hz, 1H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 192.7, 136.3, 134.7, 133.6, 130.5, 130.4, 130.0, 129.2, 129.1, 111.9, 111.3, 54.0, 26.7 ppm; IR (neat, cm^{-1}): 2916, 1682, 1595, 1493, 1449, 1256, 1223, 1094, 758, 718, 685; LRMS (ESI): *m/z* = 317 [M+H] HRMS (ESI) Calcd for $C_{17}H_{11}ClN_2ONa$: 317.0452. Found 317.0443.

*2-[1-(4-Bromophenyl)-2-phenylethyl]propanedinitrile **(3fa)***. Yield 62% (10.1 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.56 (d, *J* = 8.4 Hz, 2H), 7.38–7.25 (m, 5H), 7.18 (d, *J* = 6.8 Hz, 2H), 3.83 (d, *J* = 4.8 Hz, 1H), 3.47–3.40 (m, 1H), 3.29–3.18 (m, 2H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 136.2, 135.3, 132.4, 129.7, 129.3, 127.8, 123.3, 111.8, 111.2, 47.8, 38.4, 28.3 ppm.[7]

*Methyl 4-[2,2-Dicyano-1-(phenylmethyl)ethyl]benzoate **(3ga)***. Yield 91% (13.8 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.11–8.07 (m, 2H), 7.49–7.45 (m, 2H), 7.34–7.27 (m, 3H), 7.20–7.16 (m, 2H), 3.93 (s, 3H), 3.89 (d, *J* = 5.2 Hz, 1H), 3.55–3.51 (m, 1H), 3.51–3.25 (m, 2H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 166.4, 141.2, 136.1, 120.9, 120.4, 129.3, 128.9, 128.2, 127.8, 111.8, 111.2, 52.3, 48.2, 38.4, 28.2 ppm.[7]

*2-[1-(4-Formylphenyl)-2-phenylethyl]propanedinitrile **(3ha)***. Yield 55% (7.5 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.04 (s, 1H), 7.97–7.92 (m, 2H), 7.60–7.56 (m, 2H), 7.34 (m, 3H), 7.21–7.17 (m, 2H), 3.92 (d, *J* = 5.2 Hz, 1H), 3.60–3.53 (m, 1H), 3.36–3.23 (m, 2H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 191.5, 142.8, 136.8, 135.9, 130.4, 129.3, 128.90, 128.88, 127.9, 111.7,111.1, 48.3, 38.4, 28.1 ppm.[7]

*2-[1-(4-Cyanophenyl)-2-phenylethyl]propanedinitrile **(3ia)***. Yield 90% (12.2 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85 (d, *J* = 8.8 Hz, 2H), 7.73 (d, *J* = 8.4 Hz, 2H), 7.60 (t, *J* = 7.6 Hz, 1H), 7.51 (d, *J* = 8.4 Hz, 2H), 7.49–7.40 (m, 2H), 5.19 (d, *J* = 8.0 Hz, 1H), 4.58 (d, *J* = 7.6 Hz, 1H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 192.1, 136.9, 135.1, 133.7, 133.3, 129.6, 129.2, 117.6, 114.2, 111.5, 111.0, 54.2, 26.5 ppm; IR (neat, cm^{-1}): 2914, 2232, 1684, 1597, 1449, 1260, 1223, 758, 687; LRMS (ESI): *m/z* = 308 [M+H] HRMS (ESI) Calcd for $C_{18}H_{11}N_3ONa$: 308.0794. Found 308.0805.

*2-[1-(4-Nitrophenyl)-2-phenylethyl]propanedinitrile **(3ja)***. Yield 70% (10.2 mg), yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32–8.28 (m, 2H), 7.62–7.58 (m, 2H), 7.37–7.30 (m, 3H), 7.21–7.17 (m, 2H), 3.92 (d, *J* = 2.4 Hz, 1H), 3.64–3.57 (m, 1H), 3.36–3.23 (m, 2H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 148.4, 143.3. 135.9, 129.5, 129.3, 128.8, 128.1, 124.4, 111.5, 110.8, 47.7, 38.3, 28.0 ppm.[7]

*2-[1-(3-Methylphenyl)-2-phenylethyl]propanedinitrile **(3ka)***. Yield 79% (10.3 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36–7.27 (m, 4H), 7.22–7.17 (m, 5H), 3.83 (d, *J* = 4.8 Hz, 1H), 3.42 (td, *J* = 8.0, 4.8 Hz, 1H), 3.25 (d, *J* = 8.0 Hz, 2H), 2.39 (s, 3H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 138.9, 136.7, 136.4, 129.8, 129.1, 129.0, 128.9, 128.7, 127.6, 125.0, 112.1, 111.5, 48.3, 38.5, 28.5, 21.5 ppm; IR (neat, cm^{-1}): 3030, 2922, 2254, 2230, 1672, 1606, 1494, 1454, 1030, 786, 756, 704; LRMS (ESI): *m/z* = 283 [M+Na]; HRMS (ESI): Calcd for $C_{18}H_{16}N_2Na$: 283.1206. Found 283.1208.

*2-[1-(2-Methylphenyl)-2-phenylethyl]propanedinitrile **(3la)***.Yield 68% (8.9 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47 (d, *J* = 7.6 Hz, 1H), 7.33–7.21 (m, 5H), 7.18 (d, *J* = 7.2 Hz, 1H), 7.13–7.09 (m, 2H), 3.89–3.80 (m, 2H), 3.29 (dd, *J* = 14.0, 7.2 Hz, 1H), 3.15 (dd, *J* = 14.0, 7.2 Hz, 1H), 2.24 (s, 3H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 136.6, 136.5, 135.0, 131.2, 128.9, 128.5, 127.4, 126.9, 125.8, 112.1, 111.8, 42.9, 39.2, 28.0, 19.6 ppm; IR (neat, cm^{-1}): 3064, 3028, 2914, 2254, 1732, 1604, 1494, 1454, 1248, 1030, 762, 700, 566; LRMS (ESI): *m/z* = 283 [M+Na]; HRMS (ESI): Calcd for $C_{18}H_{16}N_2$: 283.1206. Found 283.1206.

*2-[2,2-Dimethyl-1-(phenylmethyl)propyl]propanedinitrile (**3ma**)*. Yield 59% (6.7 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40–7.27 (m, 5H), 3.87 (d, *J* = 2.0 Hz, 1H), 3.20 (dd, *J* =14.2, 4.0 Hz, 1H), 2.73 (dd, *J* = 14.4, 11.2 Hz, 1H), 2.19–2.15 (m, 1H), 1.91–1.78 (m, 1H), 1.74–1.61 (m, 1H), 1.13 (t, *J* = 7.2 Hz, 3H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 137.8, 129.22, 129.18, 127.6, 113.1, 112.2, 53.0, 34.6, 34.5, 28.2, 22.3 ppm.[7]

*5-(1,2-Diphenylethyl)-1,3-dimethyl-2,4,6(1H,3H,5H)-pyrimidinetrione (**3na**)*. Yield 70% (11.8 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40–7.37 (m, 2H), 7.34–7.19 (m, 6H), 7.10–7.04 (m, 2H), 3.88–3.82 (m, 1H), 3.61–3.52 (m, 2H), 3.21–3.04 (m, 1H), 3.04 (s, 3H), 3.01 (s, 3H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 169.0, 167.3, 150.9, 138.8, 138.2, 129.6, 128.9, 128.64, 128.59, 128.4, 127.3, 126.7, 52.3, 52.3, 37.6, 28.1, 27.9 ppm.[7]

*2-[2-(4-Methylphenyl)-1-phenylethyl]propanedinitrile (**3ac**)*. Yield 73% (9.5 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.46–7.36 (m, 5H), 7.14 (d, *J* = 8.0 Hz, 2H), 7.08 (d, *J* = 8.0 Hz, 2H), 3.84 (d, *J* = 5.2 Hz, 1H), 3.46–3.39 (m, 1H), 3.21 (d, *J* = 14.4 Hz, 2H), 2.33 (s, 3H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 137.3, 136.5, 133.5, 129.9, 129.1, 129.2, 128.8, 128.1, 112.1, 111.5, 48.4, 38.1, 28.4, 21.1 ppm.[7]

*2-[2,2-Dimethyl-1-phenylpropyl]propanedinitrile (**3ad**)*. Yield 91% (9.7 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39 (s, 5H), 4.22 (d, *J* = 5.6 Hz, 1H), 3.01 (d, *J* = 5.6 Hz, 1H), 1.11 (s, 9H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 136.2, 129.3, 128.7, 128.6, 56.8, 35.0, 28.5, 25.1 ppm.[7]

*2-[2-Methyl-1-phenylpropyl]propanedinitrile (**3ae**)*. Yield 18% (1.8 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44–7.38 (m, 3H), 7.33–7.31 (m, 2 H), 4.17 (d, *J* = 5.6 Hz, 1H), 2.86–2.82 (m, 1H), 2.42–2.37 (m, 1H), 1.14 (d, *J* = 6.4 Hz, 3H), 0.83 (d, *J* = 6.8 Hz, 3H) ppm. ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$) δ 136.6, 129.1, 128.8, 128.3, 112.1, 111.8, 53.4, 30.24, 27.8, 20.9, 20.4 ppm.[20]

*2-(2,2-Diethoxy-1-phenylethyl)propanedinitrile (**3af**)*. Yield 34% (4.4 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45–7.38 (m, 5H), 4.90 (d, *J* = 6.4 Hz, 1H), 4.39 (d, *J* = 5.6 Hz, 1H), 3.91–3.81 (m, 1H), 3.67–3.53 (m, 2H), 3.45–3.34 (m, 2H), 1.29 (t, *J* = 7.0 Hz, 3H), 1.06 (t, *J* = 7.0 Hz, 3H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 133.8, 129.1, 128.8, 112.1, 112.0, 102.4, 64.7, 64.0, 50.0, 25.7, 15.10, 15.07 ppm.[7]

4.3. General procedure of hydroacylation (Procedure II). Alkenes (0.05 mmol), **1b** (31.7 mg, 0.1 mmol) were dissolved 1,2-dichloroethane (1.0 mL), and mixture was warmed at 80 °C (by EYELA Personal Organic Synthesizer Chemistation) for 24 h. The solvent was evaporated and 1,1,2-trichloroethane was added as an internal standard and ^{1}H NMR was measured in $CDCl_3$ for the calculation of the NMR yield. Then crude products were purified by preparative TLC to give **3**. Other acylation reactions in Figure 2 were performed based on this Procedure II.

*2-(2-Oxo-1,2-diphenylethyl)propanedinitrile (**3ab**)*. Yield 86% (11.2 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.90 (d, *J* = 7.2 Hz, 2H), 7.55 (t, *J* = 7.6 Hz, 1H), 7.46–7.30 (m, 7H), 5.11 (d, *J* = 8.4 Hz, 1H), 4.54 (d, *J* = 8.4 Hz, 1H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 193.0, 134.4, 133.9, 132.1, 130.1, 129.9, 129.3, 129.0, 128.6, 112.1, 111.6, 54.8, 26.8 ppm.[19]

*2-[1-(4-Methylphenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3bb**)*. Yield 82% (11.2 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.92–7.88 (m, 2H), 7.57–7.51 (m, 1H), 7.44–7.38 (m, 2H), 7.26–7.19 (m, 4H), 5.07 (d, *J* = 8.4 Hz, 1H), 4.51 (d, *J* = 8.4 Hz), 2.32 (s, 1H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 193.1, 140.1, 134.4, 133.9, 130.8, 129.3, 129.0, 128.9, 128.4, 112.2, 111.7, 54.6, 26.9, 21.2 ppm.[7]

*2-[1-(4-Methoxylphenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3cb**)*. Yield 40% (5.8 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.89 (d, *J* = 8.4 Hz, 2H), 7.55 (t, *J* = 7.6 Hz, 1H), 7.41 (d, *J* = 7.6 Hz,

2H), 7.29–7.21 (m, 2H), 6.92 (d, J = 9.2 Hz, 2H), 5.06 (d, J = 8.4 Hz, 1H), 4.50 (d, J = 8.8 Hz, 1H), 3.78 (s, 3H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 193.1, 160.6, 134.3, 133.9, 129.9, 129.3, 128.9, 123.8, 115.5, 112.2, 111.7, 55.3, 54.2, 26.9 ppm; IR (neat, cm^{-1}): 2916, 1682, 1609, 1512, 1258, 1181, 1030, 755, 689; LRMS (ESI): m/z = 313 [M+H] HRMS (ESI) Calcd for $C_{18}H_{14}N_2O_2Na$: 313.0947. Found 313.0947.[8]

*2-[1-(4-Trifluoromethylphenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3db**)*. Yield 79% (13.0 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.90–7.86 (m, 2H), 7.72–7.66 (m, 2H), 7.62–7.56 (m, 1H), 7.51 (d, J = 8.0 Hz, 2H), 7.47–7.40 (m, 2H), 5.19 (d, J = 8.0 Hz, 1H), 4.57 (d, J = 8.0 Hz, 1H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.4, 135.8, 134.9, 133.4, 132.3 (q, $^2J_{C–F}$ = 33 Hz), 129.24, 129.17, 127.14, 127.10, 127.07, 127.0, 123.1 (q, $^1J_{C–F}$ = 271 Hz), 111.7, 111.1, 54.2 ppm; ^{19}F NMR (376 MHz, $CDCl_3$): δ −64.35 (s, 3F) ppm.[7]

*2-[1-(4-Chlorophenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3eb**)*. Yield 73% (10.8 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.87 (d, J = 8.4 Hz, 2H), 7.58 (t, J = 7.6 Hz, 1H), 7.50–7.35 (m, 4H), 7.35–7.27 (m, 2H), 5.10 (d, J = 8.0 Hz, 1H), 4.52 (d, J = 8.4 Hz, 1H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.7, 136.3, 134.7, 133.6, 130.5, 130.4, 130.0, 129.2, 129.1, 111.9, 111.3, 54.0, 26.7 ppm; IR (neat, cm^{-1}): 2916, 1682, 1595, 1493, 1449, 1256, 1223, 1094, 758, 718, 685; LRMS (ESI): m/z = 317 [M+H] HRMS (ESI) Calcd for $C_{17}H_{11}ClN_2ONa$: 317.0452. Found 317.0443.[8]

*2-[1-(4-Bromophenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3fb**)*. Yield 87% (14.8 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.89–7.85 (m, 2H), 7.60–7.53 (m, 3H), 7.46–7.40 (m, 2H), 7.26–7.22 (m, 2H), 5.08 (d, J = 8.0 Hz, 1H), 4.52 (d, J = 8.0 Hz, 1H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.6, 134.7, 133.6, 122.4, 131.0, 130.2, 129.2, 129.1, 124.5, 111.9, 111.3, 54.1, 26.6 ppm.[7]

*Methyl 4-(1-benzoyl-2,2-dicyanoethyl)benzoate (**3gb**)*. Yield 98% (15.6 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 8.11–8.07 (m, 2H), 7.90–7.85 (m, 2H), 7.60–7.54 (m, 1H), 7.47–7.39 (m, 4H), 5.16 (d, J = 8.4 Hz, 1H), 4.57 (d, J = 8.0 Hz, 1H), 3.91 (s, 3H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.5, 165.9, 136.6, 134.7, 133.6, 131.7, 131.2, 129.2, 129.1, 128.8, 111.8, 111.2, 54.6, 52.4, 26.5 ppm.[7]

*2-[1-(4-Formylphenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3hb**)*. Yield 91% (13.1 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 10.01 (s, 1H), 7.97–7.93 (m, 2H), 7.91–7.86 (m, 2H), 7.61–7.54 (m, 3H), 7.46–7.40 (m, 2H), 5.20 (d, J = 8.4 Hz, 1H), 4.60 (d, J = 8.4 Hz, 1H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.3, 190.9, 138.0, 137.2, 134.9, 133.5, 131.1, 129.5, 129.2, 129.2, 111.7, 111.1, 54.6, 26.5 ppm.[7]

*2-[1-(4-Cyanophenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3ib**)*. Yield 89% (12.7 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.85 (d, J = 8.8 Hz, 2H), 7.73 (d, J = 8.4 Hz, 2H), 7.60 (t, J = 7.6 Hz, 1H), 7.51 (d, J = 8.4 Hz, 2H), 7.49–7.40 (m, 2H), 5.19 (d, J = 8.0 Hz, 1H), 4.58 (d, J = 7.6 Hz, 1H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.1, 136.9, 135.1, 133.7, 133.3, 129.6, 129.3, 129.2, 117.6, 114.2, 111.5, 111.0, 54.2, 26.5 ppm; IR (neat, cm^{-1}): 2914, 2232, 1684, 1597, 1449, 1260, 1223, 758, 687; LRMS (ESI): m/z = 308 [M+H] HRMS (ESI) Calcd for $C_{18}H_{11}N_3ONa$: 308.0794. Found 308.0805.

*2-[1-(4-Nitrophenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3jb**)*. Yield 43% (6.6 mg), yellow oil. ^1H NMR (400 MHz, $CDCl_3$): δ 8.30 (d, J = 8.0 Hz, 2H), 7.87 (dd, J = 7.6, 1.2 Hz, 1H), 7.62–7.57 (m, 3H), 7.45 (t, J = 8.0 Hz, 2H), 5.23 (d, J = 8.0 Hz, 1H), 4.60 (d, J = 7.2 Hz, 1H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.0, 148.8, 138.6, 135.1, 133.3, 129.9, 129.3, 129.2, 125.2, 111.4, 110.9, 54.0, 26.5 ppm.[7]

*2-[1-(3-Methylphenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3kb**)*. Yield 82% (11.2 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.91 (d, J = 8.4 Hz, 2H), 7.56 (t, J = 8.0 Hz, 1H), 7.42 (t, J = 8.0 Hz, 2H), 7.35-7.10 (m, 4H), 5.07 (d, J = 8.8 Hz, 1H), 4.53 (d, J = 8.8 Hz, 1H), 2.34 (s, 3H) ppm; $^{13}C\{^1H\}$ NMR (100

MHz, $CDCl_3$): δ 193.0, 140.1, 134.4, 133.9. 131.9, 130.8, 129.9, 129.3, 129.0, 128.9, 125.8, 112.2, 111.6, 54.8, 26.9, 21.5 ppm; IR (neat, cm^{-1}): 3385, 3063, 3026, 2918, 2257, 2209, 1680, 1597, 1449, 1260, 753, 691; LRMS (ESI): *m/z* = 297 [M+H] HRMS (ESI) Calcd for $C_{18}H_{14}N_2NaO$: 297.0998. Found 297.0998.

*2-[1-(2-Methylphenyl)-2-oxo-2-phenylethyl]propanedinitrile (**3lb**)*. Yield 63% (8.6 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.77 (d, *J* = 8.4 Hz, 2H), 7.54 (t, *J* = 7.6 Hz, 1H), 7.45–7.23 (m, 4H), 7.16 (t, *J* = 7.6 Hz, 1H), 7.02 (d, *J* = 8.0 Hz, 1H), 5.34 (d, *J* = 8.8 Hz, 1H), 4.52 (d, *J* = 8.8 Hz, 1H), 2.71 (s, 3H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 193.7, 136.3, 134.4, 134.0, 132.3, 130.7, 129.9, 129.0, 128.8, 127.7, 127.2, 112.2, 111.6, 50.8, 26.1, 20.0 ppm; IR (neat, cm^{-1}): 3375, 2916, 2257, 2209, 1680, 1449, 1256, 753, 689; LRMS (ESI): *m/z* = 297 [M+H] HRMS (ESI) Calcd for $C_{18}H_{14}N_2NaO$: 297.0998. Found 297.1006.

*2-(1-Benzoyl-2,2-dimethylpropyl)propanedinitrile (**3mb**)*. Yield 26% (3.1 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.96 (dd, *J* = 10.0, 4.0 Hz, 2H), 7.66 (td, *J* = 8.0, 1.2 Hz, 1H), 7.53 (t, *J* = 8.0 Hz, 2H), 4.28 (d, *J* = 8.0 Hz, 1H), 4.07 (d, *J* = 8.0 Hz, 1H), 1.14 (s, 9H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ = 198.2, 137.4, 134.4, 129.1, 128.6, 113.2, 112.5, 54.1, 34.8, 28.6, 22.3 ppm.[7]

*1,3-Dimethyl-5-(2-oxo-1,2-diphenylethyl)-2,4,6(1H,3H,5H)-pyrimidinetrione (**3nb**)*. Yield 60% (10.5 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.79 (d, *J* = 7.2 Hz, 2H), 7.48 (t, *J* = 7.4 Hz, 1H), 7.37–7.20 (m, 7H), 5.82 (d, *J* = 3.2 Hz, 1H), 3.83 (d, *J* = 3.2 Hz, 1H), 3.33 (s, 3H), 3.30 (s, 3H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 198.1, 167.7, 167.1, 151.5, 137.0, 134.9, 133.6, 130.2, 129.4, 128.59, 128.58, 127.7, 56.7, 51.4, 28.9, 28.6 ppm.[7]

*2-Benzoyl-1,4-dihydroxynaphthalene (**3ob**)*. Yield 70% (9.2 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 13.56 (s, 1H), 8.52 (d, *J* = 8.0 Hz, 1H), 8.13 (d, *J* = 8.4 Hz, 1H), 7.77–7.40 (m, 7H), 6.86 (s, 1H), 5.10 (brs, 1H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 200.9, 158.8, 142.6, 138.2, 131.6, 130.1, 129.4, 128.9, 128.4, 126.6, 126.1, 124.7, 121.7, 111.5, 108.0 ppm.[21]

*3-Benzoylcyclohexanone (**3pb**)*. Yield 26% (2.6 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.95 (d, *J* = 7.6 Hz, 2H), 7.60 (t, *J* = 7.2 Hz, 1H), 7.49 (t, *J* = 7.6 Hz, 2H), 3.90–3.75 (m, 1H), 2.73 (dd, *J* = 14.4, 11.0 Hz, 1H), 2.54–2.30 (m, 3H), 2.20–2.05 (m, 2H), 1.95–1.78 (m, 2H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 210.2, 200.4, 135.4, 133.5, 128.9, 128.4, 45.2, 43.2, 41.0, 28.4, 24.8 ppm.[22]

*2-[2-Oxo-2-(4-methylphenyl)-1-phenylethyl]propanedinitrile (**3ag**)*. Yield 67% (9.2 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.80 (d, *J* = 8.4 Hz, 2H), 7.45–7.30 (m, 5H), 7.20 (d, *J* = 8.0 Hz, 2H), 5.08 (d, *J* = 8.4 Hz, 1H), 4.53 (d, *J* = 8.4 Hz, 1H), 2.36 (s, 3H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.6, 145.7, 132.3, 131.4, 130.0, 129.8, 129.7, 129.4, 128.6, 112.2, 111.6, 54.7, 26.8, 21.8 ppm; IR (neat, cm^{-1}): 3032, 2918, 2257, 1680, 1605, 1455, 1262, 1177, 756, 704; LRMS (ESI): *m/z* = 297 [M+H] HRMS (ESI) Calcd for $C_{18}H_{14}N_2ONa$: 297.0998. Found 297.0997.

*2-[2-Oxo-2-(4-bromophenyl)-1-phenylethyl]propanedinitrile (**3ah**)*. Yield 62% (10.5 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.75 (d, *J* = 8.8 Hz, 2H), 7.55 (d, *J* = 8.8 Hz, 2H), 7.50–7.28 (m, 5H), 5.04 (d, *J* = 8.0 Hz, 1H), 4.51 (d, *J* = 8.4 Hz, 1H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 192.1, 132.5, 131.7, 131.3, 130.6, 130.2, 130.1, 130.0, 128.6, 120.0, 111.3, 54.9, 26.8 ppm; IR (neat, cm^{-1}): 2918, 1682, 1586, 1399, 1256, 1071, 1009, 755, 701; LRMS (ESI): *m/z* = 361 [M+H] HRMS (ESI) Calcd for $C_{17}H_{11}BrN_2ONa$: 360.9947. Found 360.9947.

*2-(2-Oxo-1-phenylpropyl)propanedinitrile (**3ai**)*. Yield 88% (8.7 mg), colorless oil. ^1H NMR (400 MHz, $CDCl_3$): δ 7.51–7.45 (m, 3H), 7.30–7.24 (m, 2H), 4.37 (d, *J* = 8.4 Hz, 1H), 4.26 (d, *J* = 8.4 Hz, 1H), 2.18 (s, 3H) ppm; $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$): δ 201.4, 131.0, 130.2, 130.1, 128.7, 111.9, 111.3, 59.0, 28.3, 25.5 ppm; IR (neat, cm^{-1}): 2916, 1715, 1360, 1165, 756, 701; LRMS (ESI):

m/z = 221 [M+H] HRMS (ESI) Calcd for $C_{12}H_{10}N_2ONa$: 221.0685. Found 221.0692.

4.4. 1 mmol scale experiment. 2a (154 mg, 1 mmol), **1a** (607 mg, 2 mmol) were dissolved 2-propanol (5.0 mL), and mixture was warmed at 80 °C (oil bath) for 24 h. Then **1a** (304 mg, 1 mmol) was added to the mixture and stirred for further 48 h at 80 °C. The solvent was evaporated and then crude products were purified by silica gel column chromatography to give **3** (173 mg, 0.702 mmol, 70%).

4.5. Radical scavenging experiments. According to the general procedure of alkylation and acylation. Benzalmalononitrile **2a** (15.4 mg, 0.10 mmol), benzothiazoline **1a** or **1b** (0.20 mmol) and TEMPO (19.8 mg, 0.127 mmol) was dissolved in 2-propanol or 1,2-dichloroethane (2.0 mL), and the mixture was warmed at 80 °C for 24 h. Then crude products were purified by preparative TLC (hexane: AcOEt = 10:1) to give **4**.

*2,2,6,6-Tetramethyl-1-(phenylmethoxy)piperidine (**4a**)*. Yield 33% (8.2 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.38–7.32 (m, 4H), 7.28 (d, *J*=6.4 Hz, 1H), 4.83 (s, 2H), 1.63–1.32 (m, 6H), 1.26 (s, 6H), 1.15 (s, 6H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 138.3, 128.2, 127.5, 127.3, 78.7, 60.0, 39.7, 33.1, 20.3, 17.1 ppm.[23]

*2,2,6,6-Tetramethyl-1-piperidinyl benzoate (**4b**)*. Yield 38% (9.9 mg), colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.08 (d, *J* = 7.2 Hz, 2H), 7.58 (t, *J* = 7.4 Hz, 1H), 7.47 (t, *J* = 7.6 Hz, 2H), 1.85–1.53 (m, 4H), 1.50–1.41 (m, 1H), 1.28 (s, 6H), 1.12 (s, 6H) ppm; ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 166.4, 132.9, 129.8, 129.6, 128.5, 60.4, 39.1, 32.0, 20.9, 17.0 ppm.[24]

ASSOCIATED CONTENT

Supporting Information.

The Supporting Information is available free of charge on the ACS Publications website. Screening of detail conditions of hydroalkylation and hydroacylation, and ^{1}H and ^{13}C{^{1}H} NMR spectra (PDF)

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