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Indium-mediated Reformatsky–Claisen rearrangement

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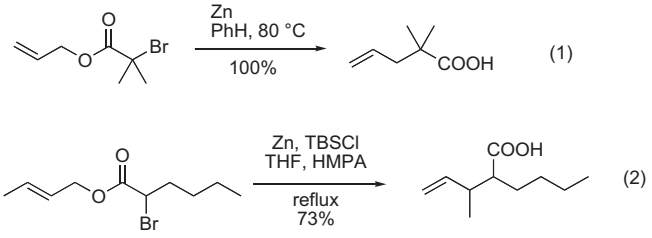
ABSTRACT

A new variant of the Reformatsky–Claisen rearrangement is described. The reaction of substituted allyl α-bromoacetates with indium and indium(III) chloride under ultrasonication provides a general entry into the functionalized synthon.

1. Introduction

Development of new methods for the stereoselective carbon–carbon bond formation has been important in the creation of useful molecules, such as drugs and other chemical entities. The [3,3]-sigmatropic rearrangements are reliable for selective bond formation, in particular, the Claisen rearrangement is one of the most competent methods to provide useful building blocks for the synthesis of natural products.[1] The versatile utilities of their products prompted the development of a considerable number of variants of the Claisen rearrangement.[2] For instance, the rearrangement of allyl α-bromoacetates with zinc dust was referred as the Reformatsky–Claisen rearrangement (Scheme 1, Eq. 1).[3] This variant of the Claisen rearrangement also proceeds in the presence of a silylating agent, in which the silyl ketene acetal is the most likely intermediate (Scheme 1, Eq. 2).[4] In the course of our synthetic study of natural products, we needed to explore a Claisen rearrangement executable under non-basic conditions. Therefore, we took a great interest in the Reformatsky–Claisen rearrangement. The Ireland–Claisen rearrangement has been widely used in the synthesis of a diverse range of natural products,[2a,4,5] whereas only several examples of zinc-mediated Reformatsky–Claisen rearrangement have been utilized so far.[6] The main reason behind encumbering the development of the Reformatsky–Claisen rearrangement arises from the accompanying side reaction, which gives the corresponding protonated products. Recently we reported In–$InCl_3$ is effective for the Reformatsky–Claisen rearrangement, but this method is feasible only for α-bromoisobutyrate derivatives.[7] Herein we report an improved method for the indium-mediated Reformatsky–Claisen rearrangement as well as the mechanistic insight of the reaction.



Scheme 1. Pioneer works of Reformatsky–Claisen rearrangement.

2. Results and discussion

2.1. Investigation of Reformatsky–Claisen rearrangement of 1

Initially, we examined the Reformatsky–Claisen rearrangement of α-bromocyclohexanecarboxylate **1** by the conventional method. However, when **1** was treated with Zn and TMSCl–Et_3N in THF, the protonated product **2** was obtained exclusively (Scheme 2). The scope of the Reformatsky reaction has been considerably extended by the development of metals other than zinc. For instance, indium is known to react readily with α-halo esters to induce the Reformatsky-type reaction.[8] Recently Baba demonstrated that In(I)X is effective for the Reformatsky-type reactions of ketones and esters to afford β-hydroxyketones and β-hydroxyesters diastereoselectively.[9] These reports prompted us to investigate the indium-mediated rearrangement of **1**. In fact, we gratifyingly found that reaction of **1** with

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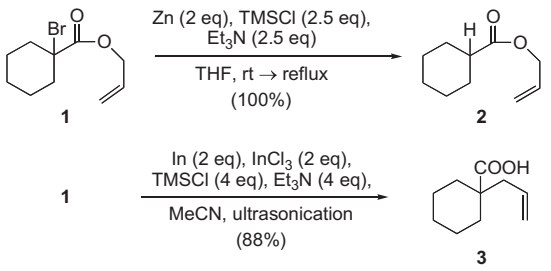
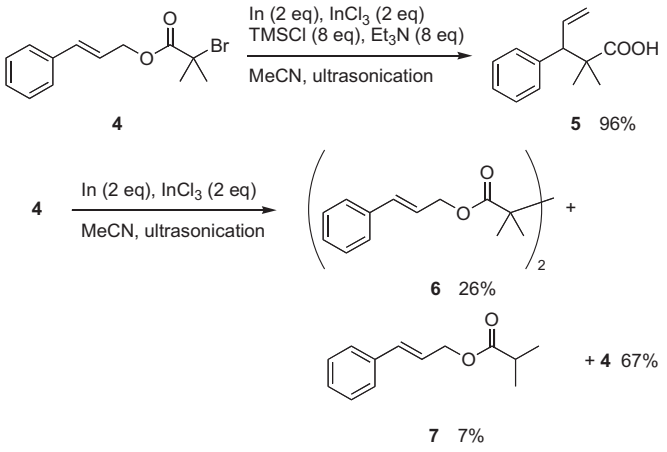
In–$InCl_3$ in the presence of TMSCl and Et_3N in MeCN under ultrasonication at 10–30 °C furnished **3** in 88% yield.



Scheme 2. Preliminary works of indium-mediated Reformatsky–Claisen rearrangement.

2.2. The effect of silylating agents

The rearrangement of bromoisobutyrate derivative **4** also proceeded smoothly to afford the rearranged product **5** in an excellent yield (Scheme 3). Baldwin and Walker reported that the zinc-mediated Reformatsky–Claisen rearrangement proceeded smoothly without a silylating agent; however, the use of TMSCl and Et_3N is requisite for the rearrangement in our case. For instance, exposure of **4** to In and $InCl_3$ without TMSCl and Et_3N furnished the homocoupling compound **6** in 26% yield, along with the protonated compound **7** and the starting material **4** in 7% and 67% yields. On the other hand, the indium-mediated reaction of **4** with TMSCl in the absence of Et_3N resulted in a complex mixture.



Scheme 3. Effect of silylating agents.

2.3. Indium-mediated Reformatsky–Claisen rearrangement of α-bromopropionate

To probe the generality of the indium-mediated reaction, α-bromopropionate **8** was next subjected to the optimized reaction conditions. As Table 1 illustrates, the reaction of **8** in MeCN was unsuccessful, resulting in the exclusive production of unwanted propionate **9** (entry 1). When MeCN-d_3 was used as a solvent, deuteration product **9a** was obtained in 63% yield (entry 2). This result suggested that a hydrogen atom installed in **9** would be delivered from MeCN, affording **9a**. It should be mentioned that this condition allowed the production of desired **10** in 37% yield presumably because of a heavy-atom effect. Considered that the formation of a silyl ketene acetal would compete with the protonation of an enolate, we next investigated several aprotic polar solvents and indium species for the reaction of **8**. Pivalonitrile, having less acidic methyl group, was utilized as a solvent; however, only product **9** was again generated (entry 3). On the other hand, the reaction in THF afforded **10** in 32% yield, but the major product was **9** (entry 4). By the use of a 4:1 mixture of THF and DMPU as a solvent, the yield of the rearranged product **10** was much improved (entry 5). In addition, we were pleased to find that the reaction in a 1:1 mixture of THF and DMPU brought us the satisfying result, giving **10** in 84% yield together with **9** (16% yield) (entry 6). The use of DMPU alone led to the small decline of the yield of **10** (entry 7). In contrast, treatment of **8** with indium(III) triflate and indium in THF–DMPU (1:1) afforded **9** quantitatively (entry 8). The combination of indium(III) bromide and indium was also found to be effective in the rearrangement (entry 9), providing **10** in 83% yield, whereas indium(I) chloride turned out to be ineffective (entry 10).

2.4. Indium-mediated Reformatsky–Claisen rearrangement of various substrates

We next turned our attention to the reaction of various α-bromopropionate derivatives, which are readily prepared by acylation of allylic alcohols with 2-bromoisobutyryl bromide or 2-bromopropionyl bromide (Table 2). Most reactions afforded rearranged products along with the protonated compounds

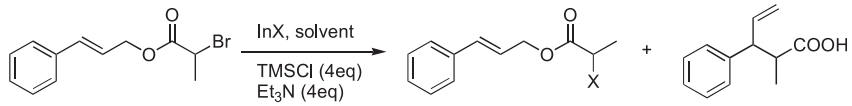
The aromatic compounds **11**, **13**, **15**, and **17** underwent rearrangement to carboxylic acids **12**, **14**, **16**, and **18**, in moderate to excellent yields (entries 1–4). However, the diastereoselectivities were poor (entries 2 and 4). In the case of **11** and **15**, the rearrangement took place in MeCN rather smoothly, whereas the rearrangement of **13** and **17** proceeded in THF–DMPU (1:1) but not in MeCN. Interestingly, 4-nitrocinnamyl derivative **19** did not give the rearranged product **20** at all (entry 5). On the other hand, the reactions of aliphatic substrates **21**–**29** brought about the Reformatsky–Claisen rearrangement successfully to give highly functionalized carboxylic acids **22**–**30** (entries 6–10). In fact, when the indium-mediated reaction of bulky 2-methylbut-3-en-2-yl esters **21** and **23** were performed, compounds **22** and **24** were yielded in 63% and 62% yields, respectively. Notably, the rearrangement of **25** can install the contiguous quaternary centers, giving compound **26** in 91% yield. In addition, propargyl ester **29** was converted to 1,1-disubstituted allenic compound **30** in 60% yield. In contrast, the reactions of the cyclic α-bromoisobutyrate **31** and **33** gave the corresponding carboxylic acids **32** and **34** in low yields. These disappointing results can be rationalized by the transition states, which involve highly strained boat forms.

To illustrate the application of the indium-mediated rearrangement to the complicated substrates, α-bromocarboxylates **35**, **37**, and **39** were prepared by esterification of cinnamyl alcohol and the corresponding α-bromocarboxylic acids,[10] which were available in a single step ($NaNO_2$, KBr, aq H_2SO_4) from L-phenylalanine,[11a] L-valine,[11b] and L-isoleucine.[11c] It turned out that indium-mediated rearrangements of **35**, **37**, and **39** provided functionalized carboxylic acids **36**, **38**, and **40** in 53%, 63%, and 73% yields, respectively, though the diastereoselectivities were not satisfying (Table 3). For an extensive survey of the reactions of dialkylated bromoacetates,[12] the indium-mediated reaction of **41** gave carboxylic acid **42** in 77% yield, whereas the reaction of **43** afforded the rearrangement product **44** in low yield (entries 4 and 5). The diastereoselectivities of both reactions were again poor. It should be mentioned that the rearrangement of chiral **35** afforded racemic compound **36**. This result implies the reaction did not proceed through a radical intermediate, which was derived from organoindium species, but [3,3]-sigmatropic rearrangement of the ketene acetal (Table 3).

2.5. The reaction of acyloxy and base-sensitive compounds

The most intriguing feature of the Reformatsky–Claisen rearrangement is the feasibility of utilizing base-sensitive substrates.

Table 1
Investigation of the Reformatsky–Claisen rearrangement of α-bromopropionate **8**

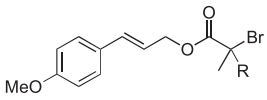
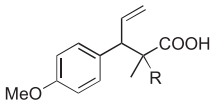
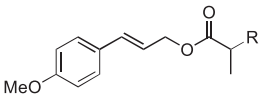
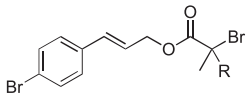
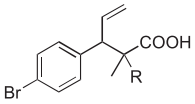
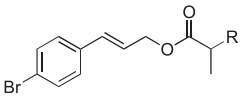
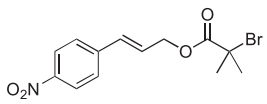
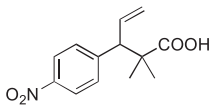
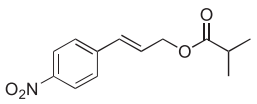
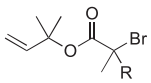
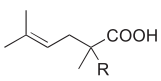
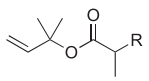
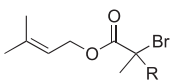
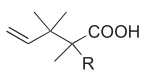
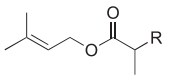
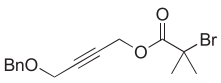
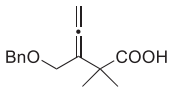
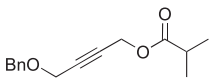
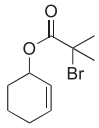
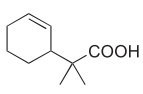
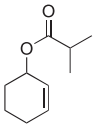
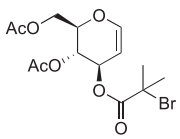
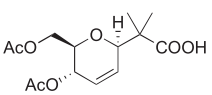
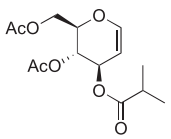


8 **9** X = H, **9a** X = D **10**

Entry	Indium source	Solvents	Yield[a] (%)	
			9	**10** (diastereomeric ratio[b])
1	In (2 equiv), $InCl_3$ (2 equiv)	MeCN	100	
2	In (2 equiv), $InCl_3$ (2 equiv)	MeCN-d_3	63 (**9a**)	37 (1.9: 1)
3	In (2 equiv), $InCl_3$ (2 equiv)	Me_3CCN	80	
4	In (2 equiv), $InCl_3$ (2 equiv)	THF	68	32 (2:1)
5	In (2 equiv), $InCl_3$ (2 equiv)	THF-DMPU (4:1)	33	60 (2:1)
6	In (2 equiv), $InCl_3$ (2 equiv)	THF-DMPU (1:1)	16	84 (1.5:1)
7	In (2 equiv), $InCl_3$ (2 equiv)	DMPU	18	77 (1.5:1)
8	In (2 equiv), $In(OTf)_3$ (2 equiv)	THF-DMPU (1:1)	100	
9	In (2 equiv), $InBr_3$ (2 equiv)	THF-DMPU (1:1)	17	83 (2:1)
10	InCl (2eq.)	THF-DMPU (1:1)	27	22 (2.3:1)

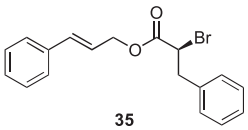
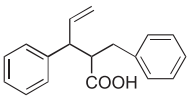
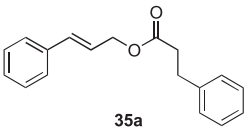
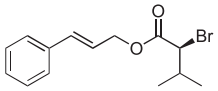
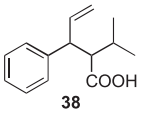
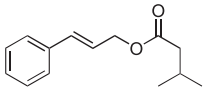
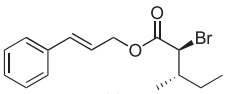
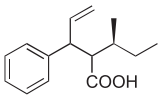
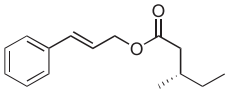
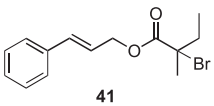
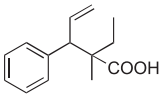
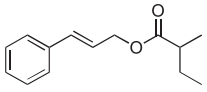
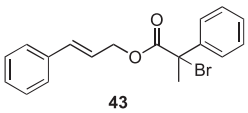
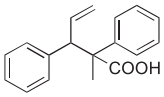
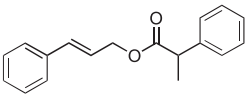
[a] Isolated yields.
[b] Determined by ^1H NMR spectra. The relative structures of the diastereomeric isomers were not determined.

Table 2
Reformatsky–Claisen rearrangement of various substrates **11**–**33**

Entry	Substrates	R	Yield[c] (%)			
			Rearranged products (diastereomeric ratio[d])		Protonated products	
1[a]		**11** Me		**12** 94		**11a** ND[e]
2[b]		**13** H		**14** 61 (1.6:1)		**13a** 32
3[a]		**15** Me		**16** 71		**15a** 25
4[b]		**17** H		**18** 54 (1.4:1)		**17a** 44
5[a]		**19** Me		**20** ND[e]		**19a** ND[e]
6[a]		**21** Me		**22** 63		**21a** ND[e]
7[b]		**23** H		**24** 62		**23a** 24
8[a]		**25** Me		**26** 91		**25a** ND[e]
9[b]		**27** H		**28** 34		**27a** 62
10[a]		**29**		**30** 60		**29a** 36
11[a]		**31**		**32** 15		**31a** 36
12[a]		**33**		**34** 35		**33a** 56

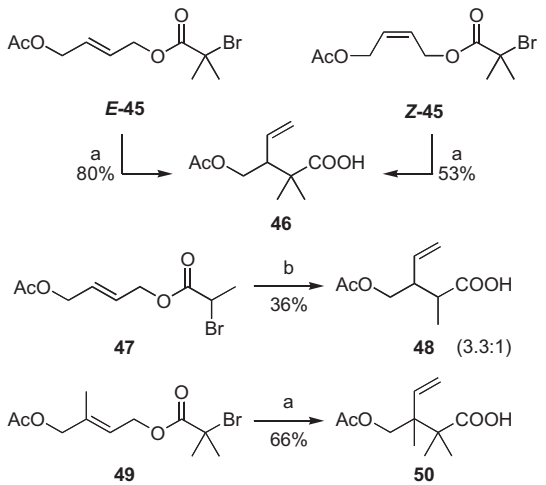
[a] The reactions were carried out by using In (2 equiv), $InCl_3$ (2 equiv), TMSCl (8 equiv), and Et_3N (8 equiv) in MeCN under ultrasonication.
[b] The reactions were carried out by using In (2 equiv), $InCl_3$ (2 equiv), TMSCl (4 equiv), and Et_3N (4 equiv) in THF-DMPU (1:1) under ultrasonication.
[c] Isolated yields.
[d] Determined by ^1H NMR spectra. The relative structures of the diastereomeric isomers were not determined.
[e] Not detected.

Table 3
Reformatsky–Claisen rearrangement of various substrates **35**–**43**[a]

Entry	Substrates	Yield[b] (%)		
		Rearranged products (diastereomeric ratio[c])		Protonated products %
1	 **35**	 **36**	53% (2.0:1)	 **35a**	42
2	 **37**	 **38**	63% (2.0:1)	 **37a**	27
3	 **39**	 **40**	73% (2.4:2.2:1.1:1.0)	 **39a**	11
4	 **41**	 **42**	77% (1.5:1)	 **41a**	22
5	 **43**	 **44**	19% (1.0:1.3)	 **43a**	81

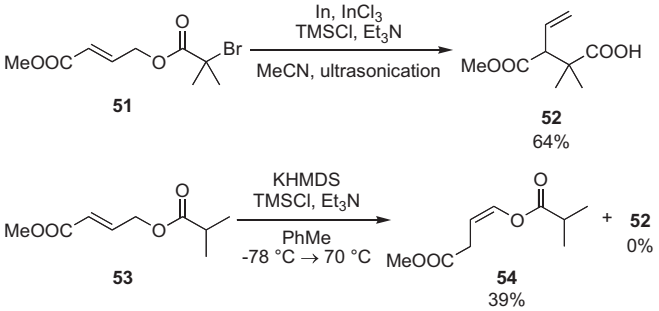
[a] The reactions were carried out by using In (2 equiv), $InCl_3$ (2 equiv), TMSCl (4 equiv), and Et_3N (4 equiv) in THF-DMPU (1:1) under ultrasonication.
[b] Isolated yields.
[c] Determined by ^1H NMR spectra. The relative structures of the diastereomeric isomers were not determined.

The reactions of α-bromoisobutyrates *E*-**45** and *Z*-**45** under the optimized conditions proceeded smoothly to afford **46** in 80% and 53% yields, respectively (Scheme 4). In the case of bromopropionate **47**, the moderate diastereoselectivity was observed, although the yield was not satisfying. On the other hand, the reaction of **49** afforded carboxylic acid **50** having contiguous quaternary carbons in 66% yield. It should be noted that the acetoxy group could survive under the reaction conditions in stark contrast to Ireland–Claisen rearrangement.



Scheme 4. Reagents and conditions; (a) In (2 equiv), $InCl_3$ (2 equiv), TMSCl (8 equiv), Et_3N (8 equiv), MeCN, ultrasonication; (b) In (2 equiv), $InCl_3$ (2 equiv), TMSCl (4 equiv), Et_3N (4 equiv), THF–DMPU (1:1), ultrasonication.

The results shown in Scheme 5 revealed a marked advantage over the Ireland–Claisen rearrangement. Thus, when compound **51** was subjected to the above mentioned indium-mediated rearrangement conditions, the rearranged product **52** was obtained in 64% yield. In contrast, the reaction of **53** with KHMDS in the presence of TMSCl and Et_3N afforded isomer **54**[13] in place of **52**.

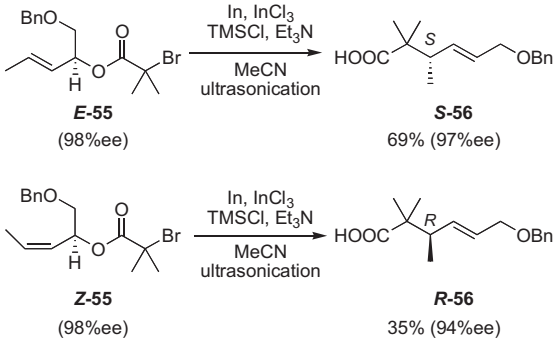


Scheme 5. Attempted rearrangements of **51** and **53**.

2.6. Potential for the chirality transfer of the Reformatsky–Claisen rearrangement

An efficient chirality transfer is often observed in the Claisen rearrangement owing to its fixed chair transition state. To demonstrate a potential for the chirality transfer, the indium-mediated rearrangement of chiral compounds *E*-**55** and *Z*-**55** were explored (Scheme 6). The compounds *E*- and *Z*-**55** in 98% ee were derived from chiral benzyl glycidol in five steps.[14] The Reformatsky–Claisen rearrangement of *E*-**55** provided *S*-**56** in 97% ee and 69% yield, and the reaction of *Z*-**55** afforded *R*-**56** in 94% ee and 35% yield. Notably,

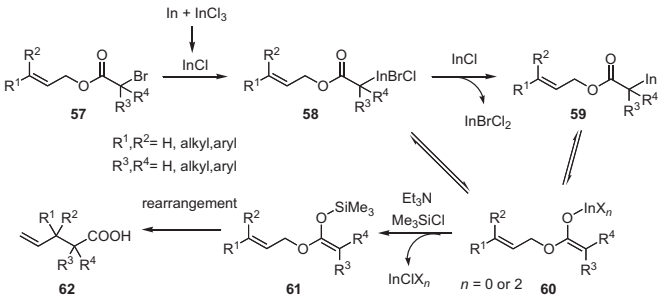
the significant loss of the enantiomeric purity of the substrates was not observed in these cases. These results suggest that this Claisen rearrangement would proceed through a chair form transition state to completely transfer the chirality of the substrate to the product.



Scheme 6. Reformatsky–Claisen rearrangements of *E*- and *Z*-**55**.

2.7. Proposed mechanism of indium-mediated Reformatsky–Claisen rearrangement

As illustrated in Scheme 7, it has been reported that a mixture of In and $InCl_3$ generates in situ InCl(I), which readily reacts with α-bromoacetate **57** to afford α-In(III) intermediate **58** or α-In(I) **59**.[9] Both α-indium intermediates can be transformed to indium enolate **60**, which is converted to silyl ketene acetal **61** by silylation. Since no rearrangement was observed without TMSCl and Et_3N, the direct rearrangement of indium enolates is unlikely. Finally, the rearrangement of **61** proceeds to generate the corresponding carboxylic acid **62**. The rearrangement of α-bromoisobutyrate derivatives (R_3, R_4=Me) smoothly proceeded in MeCN, whereas the reaction of α-bromopropionates (R_3=Me, R_4=H) in MeCN afforded only the protonated products. These results can be rationalized as follows. Compared to enolate **60** (R_3, R_4=Me) derived from isobutyrate, the enolate **60** derived from the propionate derivative (R_3=Me, R_4=H) is more nucleophilic, so that it easily undergoes protonation with MeCN to form protonated product. The deuteration experiment of **8** in MeCN-d_3 (Table 1, entry 2) clearly supported that the rearrangement would proceed, provided that the protonation of enolate is relatively slow.



Scheme 7. Proposed mechanism of Reformatsky–Claisen rearrangement.

3. Conclusion

In conclusion, the indium-mediated Reformatsky–Claisen rearrangement of α-bromoacetate derivatives has been described. This method was found to be feasible to install the quaternary centers in product. The feasibility of this method for base-sensitive substrates makes it complementary to the Ireland–Claisen rearrangement, and allows a simple access to valuable building blocks for the synthesis of complex natural products. Further exploration of this chemistry is underway in our laboratory.

4. Experimental section

4.1. General information

Solvents and reagents were dried and distilled before use. Tetrahydrofuran (THF) and toluene (PhMe) were distilled from sodium benzophenone ketyl. CH_2Cl_2, pyridine, and Et_3N were distilled from CaH_2. DMSO was distilled under reduced pressure from CaH_2. EtOH and MeOH were distilled from their magnesium alkoxides. Normal reagent-grade solvents were used for flash chromatography and extraction. All reactions were monitored by TLC with precoated Silica gel plates (Merck, silica gel 60 F_{254} 1.05715.25). Visualization was achieved via UV light, a 5.6% ethanolic *p*-anisaldehyde solution containing 5.6% of concentrated H_2SO_4-heat, and 10% ethanolic phosphomolybdic acid solution-heat. For flash chromatography was utilized Silica gel (YMG, silica gel SIL-60-400/230W or Kanto Kagaku, silica gel 60N, spherical neutral, 37563-84). Melting points were measured in open capillary tubes and are uncorrected. IR spectra were obtained on a Hitachi model 270-30 and JASCO model FT/IR-230 infrared spectrophotometer in neat state. The ^1H NMR spectra were recorded on a JEOL model AL-300 (300 MHz), α-400 (400 MHz) and a VARIAN model Gemini 300 (300 MHz) spectrometers in $CDCl_3$. The ^{13}C NMR spectra were measured on a VARIAN Gemini 300 (75 MHz), Unity plus 500 (125 MHz), and spectrometer in $CDCl_3$. Chemical shifts (δ) were reported with tetramethylsilane (δ=0.00 ppm) or $CHCl_3$ (δ=7.26 ppm) as internal standards. Splitting patterns were designated as 's, d, t, q, m, and br'; indicating 'singlet, doublet, triplet, quartet, multiplet, and broad', respectively. Optical rotations were recorded on JASCO model DIP-370 and P-1020 digital polarimeters using $CHCl_3$ as a solvent. High-resolution mass spectra were obtained on a JEOL model JMS-HX-110 and JMS-DX303 mass spectrometer under EI condition. All reactions were carried out under anhydrous conditions and argon atmosphere, unless otherwise noted.

4.2. Typical procedure under condition a

A mixture of TMSCl (0.7 mL, 5.5 mmol) and Et_3N (0.7 mL, 5.0 mmol) was centrifuged at 3000 rpm for 5 min. The supernatant (0.72 mL, containing 2.8 mmol of TMSCl and 2.6 mmol of Et_3N) was added to a mixture of dried $InCl_3$ (156 mg, 0.72 mmol) and In (81 mg, 0.72 mmol) in CH_3CN (2 mL). To a stirred mixture was added a solution of **4** (100 mg, 0.35 mmol) in CH_3CN (3 mL) and the reaction mixture was stirred at 10–30 °C for 3 h under ultrasonication. The stirring mixture was diluted with satd NH_4Cl (4 mL), and the aqueous layer was extracted with AcOEt (30 mL×3). Drying over $MgSO_4$, concentration, and chromatography (SiO_2 15 g, hexane–EtOAc, 8:1) afforded **5** (69 mg, 0.34 mmol, 96%).

4.3. Typical procedure under condition b

A mixture of TMSCl (0.34 mL, 2.7 mmol) and Et_3N (0.34 mL, 2.5 mmol) was centrifuged at 3000 rpm for 5 min. The supernatant (0.34 mL, containing 1.4 mmol of TMSCl and 1.3 mmol of Et_3N) was added to a mixture of dried $InCl_3$ (152 mg, 0.69 mmol) and In (79 mg, 0.69 mmol) in THF (1.7 mL). To a stirred mixture was added a solution of **8** (92 mg, 0.34 mmol) in DMPU (1.7 mL) and the reaction mixture was stirred at 10–30 °C for 4 h under ultrasonication. The stirring mixture was diluted with satd NH_4Cl (15 mL) and extracted with AcOEt (15 mL×2). Combined organic extracts were washed with 1M HCl (15 mL), dried over $MgSO_4$, and concentrated. The residue was purified by chromatography (SiO_2 11 g, hexane–EtOAc, 5:1 to 1:1) afforded **10** (61 mg, 0.29 mmol, 84%) and **9** (11 mg, 0.05 mmol, 16%).

4.4. Preparation of substrates and indium-mediated Reformatsky–Claisen rearrangements

*4.4.1. Allyl 1-bromocyclohexanecarboxylate (**1**).* A mixture of cyclohexanecarboxylic acid (1.50 g, 11.7 mmol) and thionyl chloride (1.07 mL, 14.8 mmol) was heated at 90 °C for 2 h. After cooling to room temperature, phosphorous red (18.0 mg, 0.58 mmol) was added to the mixture. The reaction mixture was stirred at 90 °C for 2 h, and 2-methyl-2-butene (2.1 mL, 19.0 mmol) was added. After 20 min, to the mixture was added allyl alcohol (0.875 μl, 12.0 mmol), and stirring was continued for 2 h. The reaction mixture was diluted with H_2O (2 mL) and extracted with Et_2O (50 mL). The organic extracts were dried over Mg_2SO_4 and concentrated. The residue was purified by chromatography (SiO_2 75 g, hexane–AcOEt, 65:1) afforded **1** (2.24 g, 9.0 mmol, 78%) as a brown oil; IR (neat), ν_{max} 3455, 3083, 2955, 2667, 1744, 1644, 1438, 822, 694, 555 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.99–5.90 (m, 1H), 5.40 (d, *J* 16.1 Hz, 1H), 5.27 (d, *J* 10.4 Hz, 1H), 4.72 (d, *J* 7.2 Hz, 1H), 2.18 (br s, 4H), 1.52 (m, 4H), 1.26 (t, *J* 7.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.4, 131.4, 118.2, 65.8, 37.7, 24.5, 23.5; HRMS (EI) *m*/*z* 167 (100), 248 (M^+); HRMS (EI) calcd for $C_{10}H_{15}BrO_2$ (M^+) 248.0226, found 248.0235.

*4.4.2. 1-Allylcyclohexanecarboxylic acid (**3**).* A colorless oil; IR (neat), ν_{max} 3400 (br), 2940, 2859, 1702, 1448, 1255, 1051, 925, 844, 761 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.81–5.70 (m, 1H), 5.08 (d, *J* 16.8 Hz, 1H), 5.04 (d, *J* 11.6 Hz, 1H), 2.28 (d, *J* 7.6 Hz, 2H), 1.46–1.35 (m, 2H), 1.30–1.26 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.6, 133.3, 117.7, 47.1, 44.3, 43.1, 33.4, 25.3, 22.9; HRMS (EI) *m*/*z* 123, 168 (M^+); HRMS (EI) calcd for $C_{10}H_{16}O_2$ (M^+) 168.1151, found 168.1126.

*4.4.3. Cinnamyl 2-bromo-2-methylpropanoate (**4**).* To a solution of cinnamyl alcohol (100 mg, 0.75 mmol) in CH_2Cl_2 (2.5 mL) were added DMAP (9.0 mg, 0.08 mmol), pyridine (0.18 mL, 2.24 mmol), and 2-bromoisobutyryl bromide (0.14 mL, 1.12 mmol) at 0 °C. After stirring at 0 °C for 1.5 h, the mixture was diluted with brine (12 mL) and extracted with AcOEt (30 mL×3). Combined organic extracts were dried over Mg_2SO_4 and concentrated. The residue was purified by chromatography (SiO_2 15 g, hexane–AcOEt, 7:1) afforded **4** (229 mg, 0.81 mmol, quantitatively) as a colorless oil. IR (neat), ν_{max} 2977, 1816, 1742, 1462, 1389, 1279, 1170, 968, 746, 693, 490 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.26 (m, 5H), 6.72 (d, *J* 15.9 Hz, 1H), 6.30 (dt, *J* 6.5, 15.9 Hz, 1H), 4.83 (d, *J* 6.6 Hz, 2H), 1.97 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.3, 136.0, 134.5, 128.5, 128.1, 126.6, 122.2, 66.4, 55.7, 30.7; HRMS (EI) *m*/*z* 282 (M^+); HRMS (EI) calcd for $C_{13}H_{15}{}^{79}BrO_2$ (M^+) 282.0255, found 282.0247.

*4.4.4. 2,2-Dimethyl-3-phenylpent-4-enoic acid (**5**).* A white crystal; mp 79.5–80.3 °C; IR (neat), ν_{max} 2980, 1698, 1470, 1413, 1281, 1184, 926, 742, 706, 513 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.20–7.31 (m, 5H), 6.25 (dt, *J* 17.6, 9.6 Hz, 1H), 5.15 (dd, *J* 0.6, 10.9 Hz, 1H), 5.14 (d, *J* 0.6, 17.5 Hz, 1H), 3.63 (d, *J* 9.6 Hz, 1H), 1.18 (s, 3H), 1.13 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 183.9, 140.0, 136.6, 129.3, 128.0, 126.8, 117.8, 57.3, 46.7, 23.2, 21.8; MS (EI) *m*/*z* 204 (M^+); HRMS (EI) calcd for $C_{13}H_{16}O_2$ (M^+) 204.1150, found 204.1146.

*4.4.5. Cinnamyl 2-bromopropanoate (**8**).* To a solution of cinnamyl alcohol (2.10 g, 14.9 mmol) in CH_2Cl_2 (30 mL) were added DMAP (182 mg, 1.50 mmol), pyridine (2.4 mL, 30 mmol), and 2-bromopropionyl bromide (1.9 mL, 18 mmol) at 0 °C. After stirring at 0 °C for 40 min, the mixture was diluted with brine (100 mL) and extracted with AcOEt (100 mL×2). Combined organic extracts were dried over Mg_2SO_4 and concentrated. The residue was purified by chromatography (SiO_2 200 g, hexane–AcOEt, 20:1) afforded **8** (3.99 mg, 14.8 mmol, 98%) as a colorless oil; IR (neat), ν_{max} 3026, 1737, 1447, 1334, 1218, 1156, 968, 746, 692 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.27 (m, 5H), 6.71 (d, *J* 15.9 Hz, 1H), 6.29 (dt, *J* 15.9, 6.3 Hz, 1H), 4.83 (d, *J* 6.3 Hz, 2H), 4.42 (q, *J* 7.0 Hz, 1H), 1.86 (d, *J* 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.3, 136.3, 135.2, 128.5, 127.0, 122.5, 66.8, 40.3, 22.0; HRMS (EI) *m*/*z* 91, 115, 117, 143, 189 (100), 268 (M^+); HRMS (EI) calcd for $C_{12}H_{13}{}^{81}BrO_2$ (M^+) 270.0079, found 270.0087.

*4.4.6. 2-Methyl-3-phenylpent-4-enoic acid (**10**).* A white crystal; IR (neat), ν_{max} 2980, 1715, 1493, 1456, 1417, 1291, 919, 759, 700, 517 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.33–7.17 (m, 5H), 6.06–5.90 (m, 1H), 5.16–5.02 (m, 2H), 3.54 (t, *J* 9.4 Hz, 0.37×1H), 3.44 (t, *J* 9.3 Hz, 0.63×1H), 2.87–2.78 (m, 1H), 1.24 (d, *J* 7.1 Hz, 0.37×3H), 1.00 (d, *J* 7.1 Hz, 0.63×3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 182.2, 182.6, 142.0, 140.9, 139.3, 138.1, 128.7, 128.5, 128.1, 127.6, 126.8, 126.7, 117.0, 115.8, 53.3, 53.1, 45.1, 44.7, 15.8, 15.3; HRMS (EI) *m*/*z* 190 (M^+), 117 (100), 115; HRMS (EI) calcd for $C_{12}H_{14}O_2$ (M^+) 190.0994, found 190.0976.

*4.4.7. 4-Methoxycinnamyl 2-bromo-2-methylpropanoate (**11**).* A pale yellow oil; IR (neat), ν_{max} 2933, 1738, 1607, 1513, 1463, 1389, 1274, 1167, 1035, 965, 846 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.35 (d, *J* 8.8 Hz, 2H), 6.87 (d, *J* 8.8 Hz, 2H), 6.66 (d, *J* 15.9 Hz, 1H), 6.17 (dt, *J* 6.6, 15.9 Hz, 1H), 4.81 (dd, *J* 1.1, 6.6 Hz, 2H), 3.82 (s, 3H), 1.96 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.4, 159.6, 134.4, 128.7, 127.9, 119.9, 113.9, 66.7, 55.8, 55.2, 30.7; MS (EI) *m*/*z* 312(M^+); HRMS (EI) calcd for $C_{14}H_{17}{}^{79}BrO_3$ (M^+) 312.0361, found 312.0354.

*4.4.8. 3-(4-Methoxyphenyl)-2,2-dimethylpent-4-enoic acid (**12**).* A white crystal; mp 93.0–94.5 °C; IR (neat), ν_{max} 2979, 1702, 1611, 1513, 1469, 1250, 1180, 1037, 922, 832, 540 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.13 (d, *J* 8.8 Hz, 2H), 6.83 (d, *J* 8.8 Hz, 2H), 6.21 (dt, *J* 17.6, 10.1 Hz, 1H), 5.13 (d, *J* 11.0 Hz, 1H), 5.12 (dd, *J* 0.9, 15.9 Hz, 1H), 3.71 (s, 3H), 3.59 (d, *J* 9.6 Hz, 1H), 1.17 (s, 3H), 1.12 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 183.7, 158.4, 136.9, 132.0, 130.2, 117.5, 113.4, 56.5, 55.1, 46.8, 23.1, 21.8; MS (EI) *m*/*z* 234 (M^+); HRMS (EI) calcd for $C_{14}H_{18}O_3$ (M^+) 234.1255, found 234.1237.

*4.4.9. 4-Methoxycinnamyl 2-bromopropanoate (**13**).* A colorless oil; IR (neat), ν_{max} 2941, 1739, 1606, 1512, 1449, 1253, 1158, 972, 844, 747 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.34 (d, *J* 8.8 Hz, 2H), 6.86 (d, *J* 8.8 Hz, 2H), 6.65 (d, *J* 15.9 Hz, 1H), 6.15 (dt, *J* 15.9, 6.6 Hz, 1H), 4.80 (d, *J* 6.6 Hz, 2H), 4.40 (q, *J* 6.9 Hz, 1H), 3.81 (s, 3H), 1.85 (d, *J* 6.9 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.1, 159.7, 134.8, 128.7, 128.0, 119.8, 114.0, 66.8, 55.3, 40.1, 21.7; HRMS (EI) *m*/*z* 91, 135, 147 (100), 219, 298 (M^+); HRMS (EI) calcd for $C_{13}H_{15}{}^{79}BrO_3$ (M^+) 298.0205, found 298.0202.

*4.4.10. 3-(4-Methoxyphenyl)-2-methylpent-4-enoic acid (**14**).* A white crystal; IR (neat), ν_{max} 2981, 1722, 1511, 1461, 1264, 1035, 921, 830, 659, 541 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.13 (d, *J* 8.8 Hz, 0.39×2H), 7.09 (d, *J* 8.8 Hz, 0.61×2H), 6.85 (d, *J* 8.8 Hz, 0.61×2H), 6.82 (d, *J* 8.8 Hz, 0.39×2H), 6.04–5.85 (m, 1H), 5.13–5.00 (m, 2H), 3.77 (d, *J* 8.0 Hz, 3H), 3.49 (t, *J* 9.3 Hz, 0.39×1H), 3.40 (t, *J* 9.3 Hz, 0.61×1H), 2.82–2.74 (m, 1H), 1.23 (d, *J* 6.8 Hz, 0.39×3H), 1.00 (d, *J* 6.8 HZ, 0.61×3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.0, 181.4, 158.4, 158.2, 139.6, 138.4, 134.1, 132.9, 129.0, 128.6, 116.6, 115.4, 114.1, 113.9, 55.2, 55.2, 52.3, 52.3, 45.1, 44.8, 15.7, 15.4; HRMS (EI) *m*/*z* 220 (M^+), 147 (100), 132, 115, 91, 77; HRMS (EI) calcd for $C_{13}H_{16}O_3$ (M^+) 220.1100, found 220.1087.

*4.4.11. 4-Bromocinnamyl 2-bromo-2-methylpropanoate (**15**).* A white crystal; mp 40.5–42.0 °C; IR (neat), ν_{max} 2930, 1743, 1487, 1371, 1280, 1170, 968, 847, 643, 498 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.46 (d, *J* 8.5 Hz, 2H), 7.27 (d, *J* 8.5 Hz, 2H), 6.65 (d, *J* 15.9 Hz, 1H), 6.29 (dt, *J* 6.3, 15.9 Hz, 1H), 4.82 (d, *J* 6.2 Hz, 2H), 1.96 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.4, 135.0, 133.1, 131.7, 128.1, 123.2, 122.0, 66.1, 55.7, 30.7; HRMS (EI) *m*/*z* 360 (M^+); HRMS (EI) calcd for $C_{13}H_{14}{}^{79}Br_2O_2$ (M^+) 359.9361, found 359.9357.

*4.4.12. 3-(4-Bromophenyl)-2,2-dimethylpent-4-enoic acid (**16**).* A white crystal; mp 102.0–103.0 °C; IR (neat), ν_{max} 2980, 1707, 1489,

1404, 1276, 1076, 1011, 925, 828, 516 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42 (d, *J* 8.5 Hz, 2H), 7.09 (d, *J* 8.5 Hz, 2H), 6.18 (dt, *J* 16.8, 9.9 Hz, 1H), 5.17 (dd, *J* 0.9, 11.2 Hz, 1H), 5.14 (d, *J* 0.8, 16.7 Hz, 1H), 3.60 (d, *J* 9.3 Hz, 1H), 1.18 (s, 3H), 1.12 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 183.6, 139.0, 136.0, 131.2, 130.9, 120.8, 118.3, 56.6, 46.6, 22.9, 22.0; MS (EI) *m*/*z* 282 (M^+); HRMS (EI) calcd for $C_{13}H_{15}{}^{79}BrO_2$ (M^+) 282.0255, found 282.0270.

4.4.13. 4-Bromocinnamyl 2-bromopropanoate (17). A colorless oil; IR (neat), ν_{max} 2932, 1738, 1484, 1446, 1333, 1218, 1153, 1067, 968, 843 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.45 (d, *J* 8.5 Hz, 2H), 7.26 (d, *J* 8.5 Hz, 2H), 6.64 (d, *J* 15.9 Hz, 1H), 6.28 (dt, *J* 15.9, 6.3 Hz, 1H), 4.81 (d, *J* 6.3 Hz, 2H), 4.41 (q, *J* 6.9 Hz, 1H), 1.85 (d, *J* 6.9 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.9, 134.9, 133.4, 131.7, 128.1, 123.0, 122.0, 66.1, 40.0, 21.6; HRMS (EI) *m*/*z* 115, 116 (100), 142, 211, 297, 346, 348 ($M-H^+$); HRMS (EI) calcd for $C_{12}H_{12}{}^{81}Br_2O_2$ (M^+) 349.9163, found 349.9162.

*4.4.14. 3-(4-Bromophenyl)-2-methylpent-4-enoic acid (**18**).* A white crystal; IR (neat), ν_{max} 2980, 1711, 1486, 1413, 1292, 1075, 1005, 920, 818, 519 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.44 (d, *J* 8.6 Hz, 0.58×2H), 7.41 (d, *J* 8.3 Hz, 0.42×2H), 7.09 (d, *J* 8.3 Hz, 0.58×2H), 7.05 (d, *J* 8.3 Hz, 0.42×2H), 6.01–5.81 (m, 1H), 5.15–5.05 (m, 1H), 3.51–3.41 (m, 1H), 2.82–2.74 (m, 1H), 1.24 (d, *J* 7.0 Hz, 0.42×3H), 1.00 (d, *J* 6.8 Hz, 0.58×3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 181.6, 181.2, 141.0, 140.0, 138.7, 137.6, 131.8, 131.6, 129.8, 129.4, 120.7, 120.5, 117.4, 116.3, 52.5, 52.5, 44.8, 44.5, 15.7, 15.4; HRMS (EI) *m*/*z* 268 (M^+), 195, 116 (100), 115; HRMS (EI) calcd for $C_{12}H_{13}{}^{81}BrO_2$ (M^+) 270.0078, found 270.0084.

*4.4.15. 4-Nitrocinnamyl 2-bromo-2-methylpropanoate (**19**).* A yellow crystal; mp 49.0–50.0 °C; IR (neat), ν_{max} 2932, 1741, 1598, 1523, 1462, 1349, 1167, 970, 863, 740, 689 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.20 (d, *J* 8.8 Hz, 2H), 7.54 (d, *J* 8.5 Hz, 2H), 6.79 (d, *J* 15.9 Hz, 1H), 6.48 (dt, *J* 5.9, 15.9 Hz, 1H), 4.89 (dd, *J* 1.7, 5.8 Hz, 2H), 1.98 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.2, 147.1, 142.4, 131.4, 127.3, 127.1, 123.9, 65.5, 55.5, 30.6; MS (EI) *m*/*z* 327 (M^+); HRMS (EI) calcd for $C_{13}H_{14}{}^{79}BrO_4$ (M^+) 327.0107, found 327.0109.

*4.4.16. 2-Methylbut-3-en-2-yl 2-bromo-2-methylpropanoate (**21**).* A colorless oil; IR (neat), ν_{max} 2979, 1818, 1741, 1463, 1288, 1076, 928, 848, 739, 641, 486 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.08 (dd, *J* 10.9, 17.4 Hz, 1H), 5.25 (d, *J* 17.3 Hz, 1H), 5.13 (d, *J* 11.0 Hz, 1H), 1.90 (s, 6H), 1.56 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 169.9, 141.6, 113.1, 82.0, 57.0, 30.6, 25.9; MS (EI) *m*/*z* 235 (M^+); HRMS (EI) calcd for $C_9H_{16}{}^{79}BrO_2$ ($M+H^+$) 235.0333, found 235.0342.

*4.4.17. 2,2,5-Trimethylhex-4-enoic acid (**22**).* A yellow oil; IR (neat), ν_{max} 2974, 1709, 1473, 1409, 1383, 1241, 1201, 1162, 943, 557 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.12 (tt, *J* 7.7, 1.4 Hz, 1H), 2.26 (d, *J* 7.7 Hz, 2H), 1.72 (s, 3H), 1.61 (s, 3H), 1.19 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 184.7, 134.6, 119.6, 42.7, 38.4, 26.0, 24.5, 17.9; MS (EI) *m*/*z* 156 (M^+); HRMS (EI) calcd for $C_9H_{16}O_2$ (M^+) 156.1151, found 156.1131.

*4.4.18. 2-Methylbut-3-en-2-yl 2-bromopropanoate (**23**).* A colorless oil; IR (neat), ν_{max} 2983, 1739, 1448, 1342, 1229, 1127, 989, 929, 843 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 6.08 (dd, *J* 17.6, 11.0 Hz, 1H), 5.74 (d, *J* 17.6 Hz, 1H), 5.13 (d, *J* 11.0 Hz, 1H), 4.30 (q, *J* 6.8 Hz, 1H), 1.79 (d, *J* 6.8 Hz, 3H), 1.55 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.2, 142.0, 113.8, 82.8, 42.0, 26.5, 26.5, 21.9.

*4.4.19. 2,5-Dimethylhex-4-enoic acid (**24**).* A yellow oil; IR (neat), ν_{max} 2975, 1709, 1459, 1381, 1243, 1121, 937, 811, 640, 562 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.13–5.08 (m, 1H), 2.53–2.44 (m, 1H), 2.40–2.33 (m, 1H), 2.20–2.10 (m, 1H), 1.71 (s, 3H), 1.62 (s, 3H), 1.17 (d, *J* 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 182.8, 134.1, 120.9, 39.7, 31.8, 25.8, 17.8, 16.3; MS (EI) *m*/*z* 142 (M^+), 96, 81, 69 (100), 55, 41; HRMS (EI) calcd for $C_8H_{14}O_2$ (M^+) 142.0994, found 142.0986.

*4.4.20. 3-Methylbut-2-enyl 2-bromo-2-methylpropanoate (**25**).* A yellow oil; IR (neat), ν_{max} 2976, 1741, 1463, 1387, 1280, 1169, 1110, 1010, 958, 763, 648 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.36 (t, *J* 7.1 Hz, 1H), 4.67 (d, *J* 7.1 Hz, 2H), 1.93 (s, 6H), 1.75 (d, *J* 12.4 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.2, 129.3, 117.8, 62.6, 55.7, 30.5, 25.5, 17.9; MS (EI) *m*/*z* 234 (M^+); HRMS (EI) calcd for $C_9H_{16}{}^{79}BrO_2$ ($M+H^+$) 235.0334, found 235.0302.

*4.4.21. 2,2,3,3-Tetramethylpent-4-enoic acid (**26**).* A colorless oil; IR (neat), ν_{max} 2978, 1700, 1468, 1375, 1293, 1131, 1009, 915, 740, 553 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.98 (dd, *J* 17.3, 11.0 Hz, 1H), 5.04 (dd, *J* 10.7, 1.1 Hz, 1H), 5.00 (dd, *J* 17.3, 1.4 Hz, 1H), 1.16 (s, 6H), 1.10 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 183.9, 144.4, 112.5, 47.8, 40.9, 22.9, 21.4; MS (EI) *m*/*z* 156 (M^+); HRMS (EI) calcd for $C_9H_{16}O_2$ (M^+) 156.1150, found 156.1142.

*4.4.22. 3-Methylbut-2-enyl 2-bromopropanoate (**27**).* A colorless oil; IR (neat), ν_{max} 2977, 1739, 1447, 1380, 1340, 1223, 1158, 1062, 986, 933 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.36 (t, *J* 7.1 Hz, 1H), 4.66 (d, *J* 7.1 Hz, 2H), 4.37 (q, *J* 6.8 Hz, 1H), 1.82 (d, *J* 6.8 Hz, 3H), 1.77 (s, 3H), 1.73 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.2, 140.1, 117.7, 62.8, 40.3, 25.8, 21.7, 18.1; MS (EI) *m*/*z* 41, 69, 95, 109, 141 (100), 220, 223 (M^+); HRMS (EI) calcd for $C_8H_{13}{}^{79}BrO_2$ (M^+) 220.0099, found 220.0105.

*4.4.23. 2,3,3-Trimethylpent-4-enoic acid (**28**).* A yellow oil; IR (neat), ν_{max} 2972, 1708, 1462, 1416, 1286, 1243, 1082, 1005, 918, 694 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.86 (dd, *J* 17.4, 10.8 Hz, 1H), 5.02 (d, *J* 11.0 Hz, 1H), 5.00 (d, *J* 17.3 Hz, 1H), 2.39 (q, *J* 7.1 Hz, 1H), 1.12 (s, 3H), 1.10 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 181.5, 145.5, 112.1, 48.7, 38.5, 25.0, 23.6, 12.7; MS (EI) *m*/*z* 142 (M^+), 127, 97, 81, 69 (100); HRMS (EI) calcd for $C_8H_{14}O_2$ (M^+) 142.0994, found 142.0975.

*4.4.24. 4-(Benzyloxy)but-2-ynyl 2-bromo-2-methylpropanoate (**29**).* A yellow oil; IR (neat), ν_{max} 2856, 1746, 1455, 1371, 1273, 1162, 1011, 970, 742, 699 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.40–7.26 (m, 5H), 4.84 (s, 2H), 4.60 (s, 2H), 4.22 (s, 2H), 1.96 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.7, 137.0, 128.2, 127.9, 127.7, 83.2, 79.7, 71.4, 57.0, 55.0, 53.6, 30.5; MS (EI) *m*/*z* 324 (M^+); HRMS (EI) calcd for $C_{15}H_{17}{}^{79}BrO_3$ (M^+) 324.0361, found 324.0363.

*4.4.25. 3-((Benzyloxy)methyl)-2,2-dimethylpenta-3,4-dienoic acid (**30**).* A yellow oil; IR (neat), ν_{max} 2979, 1955, 1705, 1455, 1360, 1284, 1069, 851, 739, 699 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.38–7.23 (m, 5H), 4.94 (t, *J* 2.1 Hz, 2H), 4.59 (s, 2H), 4.13 (t, *J* 1.9 Hz, 2H), 1.38 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 207.4, 182.0, 137.9, 128.3, 127.7, 127.5, 104.5, 78.1, 71.9, 68.8, 43.0, 24.9; MS (EI) *m*/*z* 246 (M^+); HRMS (EI) calcd for $C_{15}H_{18}O_3$ (M^+) 246.1255, found 246.1257.

*4.4.26. Cyclohex-2-enyl 2-bromo-2-methylpropanoate (**31**).* A yellow oil; IR (neat), ν_{max} 2937, 1737, 1462, 1389, 1281, 1173, 1053, 1010, 912, 728 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.00 (dt, *J* 4.2, 10.2 Hz, 1H), 5.73 (dd, *J* 3.6, 9.9 Hz, 1H), 5.29 (d, *J* 4.3 Hz, 1H), 2.18–1.53 (m, 12H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.1, 133.2, 124.7, 69.5, 56.2, 30.6, 27.7, 24.8, 18.6; HRMS (EI) *m*/*z* 246 (M^+); HRMS (EI) calcd for $C_{10}H_{15}{}^{79}BrO_2$ (M^+) 246.0256, found 246.0241.

*4.4.27. 2-(Cyclohex-2-enyl)-2-methylpropanoic acid (**32**).* A yellow oil; IR (neat), ν_{max} 2929, 1702, 1469, 1367, 1279, 1149, 942, 859, 721, 619 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.79 (dd, *J* 10.3, 3.2 Hz, 1H), 5.53 (d, *J* 9.9 Hz, 1H), 2.60–2.46 (m, 1H), 2.20–1.40 (m, 6H), 1.26 (s,

6H); MS (EI) *m*/*z* 168 (M^+); HRMS (EI) calcd for $C_{10}H_{16}O_2$ (M^+) 168.1150, found 168.1138.

*4.4.28. 4,6-Di-O-acetyl-3-O-(2-bromo-2-methylpropionyl)-D-glucal (**33**).* A pale yellow oil; IR (neat), ν_{max} 2929, 1758, 1649, 1473, 1371, 1247, 1164, 1108, 759, 600 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.51 (d, *J* 6.0 Hz, 1H), 5.38–5.29 (m, 2H), 4.89 (dd, *J* 3.2, 6.2 Hz, 1H), 4.45 (dd, *J* 5.8, 12.1 Hz, 1H), 4.30 (dt, *J* 2.8, 6.6 Hz, 1H), 4.21 (dd, *J* 2.9, 11.9 Hz, 1H), 2.11 (s, 3H), 2.08 (s, 3H), 1.91 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.6, 169.4, 146.1, 98.0, 73.9, 69.0, 66.6, 61.3, 55.3, 30.4, 20.7.

*4.4.29. 2-((2S,5S,6R)-5,6-Dihydro-5-acetoxy-6-(acetoxymethyl)-2H-pyran-2-yl)-2-methylpropanoic (**34**).* A yellow oil; IR (neat), ν_{max} 2928, 1732, 1469, 1370, 1225, 1131, 1080, 1043, 794, 642, 605 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.85 (s, 2H), 5.26 (dd, *J* 9.2, 2.9 Hz, 1H), 4.42 (d, *J* 2.3 Hz, 1H), 4.25 (dd, *J* 11.8, 2.7 Hz, 1H), 4.17 (dd, *J* 11.8, 5.5 Hz, 1H), 3.74 (dt, *J* 2.7, 3.1 Hz, 1H), 2.09 (s, 3H), 2.07 (s, 3H), 1.20 (d, *J* 8.5 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 180.5, 171.2, 170.6, 128.6, 127.6, 78.7, 74.1, 65.4, 63.2, 46.3, 21.0, 21.7, 20.5; HRMS (EI) *m*/*z* 300 (M^+).

*4.4.30. (S)-Cinnamyl 2-bromo-3-phenylpropanoate (**35**).* A colorless oil; $[\alpha]_D^{25}$+17.2 (*c* 1.05, $CHCl_3$); IR (neat), ν_{max} 3031, 1739, 1494, 1445, 1225, 1149, 967, 742, 696, 516 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.39–7.20 (m, 10H), 6.63 (d, *J* 15.9 Hz, 1H), 6.18 (dt, *J* 15.9, 6.5 Hz, 1H), 4.77 (d, *J* 6.5 Hz, 2H), 4.44 (dd, *J* 8.5, 7.0 Hz, 1H), 3.49 (dd, *J* 14.0, 8.5 Hz, 1H), 3.27 (dd, *J* 14.0, 7.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.5, 137.0, 136.3, 135.2, 129.5, 129.0, 128.9, 128.5, 127.7, 127.0, 122.4, 66.7, 45.6, 41.5; HRMS (EI) *m*/*z* 91, 117 (100), 133, 265, 345 (M^+); HRMS (EI) calcd for $C_{18}H_{17}{}^{81}BrO_2$ (M^+) 346.0391, found 346.0383.

*4.4.31. 2-Benzyl-3-phenylpent-4-enoic acid (**36**).* A white crystal; IR (neat), ν_{max} 3029, 1707, 1495, 1445, 1250, 1077, 920, 757, 698 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) 7.39–7.02 (m, 10H), 6.10–5.95 (m, 1H), 5.25–5.18 (m, 0.33×1H), 5.18–5.01 (m, 0.67×1H), 3.59 (t, *J* 9.2 Hz, 0.33×1H), 3.51 (t, *J* 9.6 Hz, 0.67×1H), 3.08–3.01 (m, 0.33×1H), 2.84 (dd, *J* 11.9, 14.4 Hz, 0.33×1H), 2.72 (dd, *J* 13.9, 10.9 Hz, 0.67×1H), 2.57 (dd, *J* 13.7, 4.1 Hz, 0.67×1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 180.2, 179.6, 141.3, 141.0, 139.0, 138.8, 138.7, 138.4, 128.9, 128.7, 128.6, 128.5, 128.4, 127.9, 127.7, 127.0, 126.8, 126.4, 126.4, 117.3, 116.3, 53.7, 53.2, 53.1, 36.7, 36.4; MS (EI) *m*/*z* 266 (M^+), 175, 117 (100), 91; HRMS (EI) calcd for $C_{18}H_{18}O_2$ (M^+) 266.1307, found 266.1303.

*4.4.32. (S)-Cinnamyl 2-bromo-3-methylbutanoate (**37**).* A colorless oil; $[\alpha]_D^{24}$ −5.01 (*c* 1.00, $CHCl_3$); IR (neat), ν_{max} 2968, 1740, 1455, 1378, 1290, 1148, 970, 743, 697 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.24 (m, 5H), 6.71 (d, *J* 15.9 Hz, 1H), 6.29 (dt, *J* 15.9, 6.5 Hz, 1H), 4.83 (d, *J* 6.5 Hz, 2H), 4.09 (d, *J* 7.7 Hz, 1H), 2.36–2.19 (m, 1H), 1.11 (d, *J* 6.6 Hz, 3H), 1.05 (d, *J* 6.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.2, 136.0, 135.0, 128.6, 128.2, 126.7, 122.2, 66.2, 54.6, 32.3, 20.0, 19.9; MS(EI) *m*/*z* 115, 117 (100), 133, 217, 296 (M^+); HRMS (EI) calcd for $C_{14}H_{17}{}^{81}BrO_2$ (M^+) 298.0391, found 298.0400.

*4.4.33. 2-Isopropyl-3-phenylpent-4-enoic acid (**38**).* A white crystal; IR (neat), ν_{max} 2965, 1702, 1420, 1285, 1207, 917, 753, 695, 517 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.34–7.19 (m, 5H), 6.08–5.80 (m, 1H), 5.18–5.01 (m, 2H), 3.63 (t, *J* 9.9 Hz, 1H), 2.85–2.80 (m, 0.34×1H), 2.75 (dd, *J* 10.6, 4.8 Hz, 0.66×1H), 2.21–2.00 (m, 0.34×1H), 1.72–1.56 (m, 0.66H, 1H), 1.04 (dd, *J* 18.1, 6.9 Hz, 0.34×6H), 0.92 (t, *J* 7.1 Hz, 0.66×6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 177.9, 176.9, 142.4, 141.3, 139.4, 139.3, 128.8, 128.6, 127.9, 127.7, 126.7, 126.6, 116.1, 115.9, 56.0, 55.4, 50.5, 50.0, 27.8, 27.5, 22.0, 21.5, 17.1, 16.2; MS (EI) *m*/*z* 218 (M^+), 175, 117 (100), 115, 91; HRMS (EI) calcd for $C_{14}H_{18}O_2$ (M^+) 218.1307, found 218.1291.

*4.4.34. (2S,3S)-Cinnamyl 2-bromo-3-methylpentanoate (**39**).* A colorless oil; $[\alpha]_D^{24}$ −11.3 (*c* 1.06, $CHCl_3$); IR (neat), ν_{max} 2967, 1740, 1454, 1379, 1267, 1147, 969, 743, 698 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.24 (m, 5H), 6.71 (d, *J* 15.9 Hz, 1H), 6.29 (dt, *J* 15.9, 6.3 Hz, 1H), 4.83 (d, *J* 6.3 Hz, 2H), 4.14 (d, *J* 6.3 Hz, 2H), 2.14–2.00 (m, 1H), 1.83–1.69 (m, 1H), 1.39–1.24 (m, 1H), 1.02 (d, *J* 6.9 Hz, 3H), 0.92 (t, *J* 7.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 169.3, 136.0, 134.9, 128.6, 128.2, 126.6, 122.2, 66.2, 53.0, 38.3, 26.3, 16.2, 10.6; MS(EI) *m*/*z* 115, 117, 231 (100), 310, 311 (M−H^+); HRMS (EI) calcd for $C_{15}H_{19}{}^{81}BrO_2$ (M^+) 312.0548, found 312.0554.

*4.4.35. 2-sec-Butyl-3-phenylpent-4-enoic acid (**40**).* A white crystal; IR (neat), ν_{max} 3030, 2967, 1703, 1457, 1421, 1252, 1208, 920, 757, 699 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.33–7.16 (m, 5H), 6.07–5.83 (m, 1H), 5.16–4.97 (m, 2H), 3.70–3.62 (m, 1H), 2.90–2.69 (m, 1H), 1.89–1.41 (m, 1H), 1.41–1.15 (m, 1H), 1.15–0.71 (m, 7H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 180.0, 179.7, 179.1, 178.9, 142.4, 142.4, 141.4, 141.1, 139.8, 139.5, 139.2, 139.1, 128.8, 128.7, 128.5, 128.5, 127.9, 127.9, 127.7, 127.7, 126.7, 126.7, 126.5, 116.1, 116.1, 115.9, 115.6, 56.6, 56.0, 53.6, 50.2, 50.1, 49.8, 49.5, 34.8, 34.7, 34.2, 34.0, 28.7, 28.2, 24.3, 23.4, 18.0, 17.5, 14.3, 13.7, 12.4, 12.1, 12.0, 11.7; HRMS (EI) *m*/*z* 232 (M^+), 175, 117 (100), 115, 91; HRMS (EI) calcd for $C_{15}H_{230}O_2$ (M^+) 232.1463, found 232.1464.

*4.4.36. Cinnamyl 2-bromo-2-methylbutanoate (**41**).* A colorless oil; IR (neat), ν_{max} 2976, 1734, 1452, 1380, 1251, 1151, 964, 744, 692, 490 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.42–7.26 (m, 5H), 6.71 (d, *J* 15.9 Hz, 1H), 6.30 (dt, *J* 15.9, 6.6 Hz, 1H), 4.84 (d, *J* 6.6 Hz, 2H), 2.18 (q, *J* 7.3 Hz, 2H), 1.92 (s, 3H), 1.01 (t, *J* 7.3 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.1, 136.1, 134.7, 128.6, 128.6, 126.7, 122.4, 66.4, 62.1, 35.7, 27.4, 10.3; MS(EI) *m*/*z* 117 (100), 133, 217, 296 (M^+); HRMS (EI) calcd for $C_{14}H_{17}{}^{79}BrO_2$ (M^+) 296.0411, found 296.0414.

*4.4.37. 2-Ethyl-2-methyl-3-phenylpent-4-enoic acid (**42**).* A white crystal; IR (neat), ν_{max} 3081, 1713, 1460, 1410, 1268, 1163, 922, 789, 741, 704, 540 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.41–7.22 (m, 5H), 6.37–6.19 (m, 1H), 5.20–5.12 (m, 2H), 3.68 (d, *J* 10.0 Hz, 0.61×1H), 3.62 (d, *J* 9.5 Hz, 0.39×1H), 1.92–1.80 (m, 0.61×2H), 1.56–1.45 (m, 0.39×1H), 1.15 (s, 0.61×3H), 1.13 (s, 0.39×3H), 0.91 (t, *J* 7.2 Hz, 0.61×3H), 0.84 (t, *J* 7.3 Hz, 0.39×3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 183.1, 182.8, 140.6, 140.0, 137.1, 136.2, 129.5, 129.0, 128.1, 128.0, 126.8, 126.7, 118.0, 117.4, 58.1, 57.7, 51.5, 50.9, 31.2, 30.8, 16.2, 16.0, 9.2, 9.0; MS (EI) *m*/*z* 218 (M^+), 117 (100), 115, 43; HRMS (EI) calcd for $C_{14}H_{18}O_2$ (M^+) 218.1307, found 218.1299.

*4.4.38. Cinnamyl 2-bromo-2-phenylpropanoate (**43**).* A colorless oil; IR (neat), ν_{max} 3029, 1734, 1494, 1447, 1378, 1244, 1119, 965, 741, 695 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.36–7.24 (m, 10H), 6.61 (d, *J* 15.9 Hz, 1H), 6.22 (dt, *J* 15.9, 6.3 Hz, 1H), 4.84 (d, *J* 6.3 Hz, 2H), 2.32 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.7, 140.9, 136.0, 134.6, 128.6, 128.4, 128.1, 126.8, 126.6, 126.0, 122.1, 66.8, 61.9, 31.3; HRMS (EI) *m*/*z* 103, 117 (100), 132, 265, 344 (M^+); HRMS (EI) calcd for $C_{18}H_{17}{}^{79}BrO_2$ (M^+) 344.0412, found 344.0407.

*4.4.39. 2-Methyl-2,3-diphenylpent-4-enoic acid (**44**).* A white crystal; IR (neat), ν_{max} 3062, 1701, 1496, 1451, 1383, 1270, 1115, 997, 922, 702 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.45–6.85 (m, 10H), 6.34–6.21 (m, 0.43×1H), 6.01–5.89 (m, 0.57×1H), 5.18–5.11 (m, 0.43×2H), 5.00–4.89 (m, 0.57×2H), 4.34 (d, *J* 8.7 Hz, 0.57×1H), 4.23 (d, *J* 8.7 Hz, 0.43×1H), 1.62 (d, *J* 7.5 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 180.0, 179.8, 140.5, 140.1, 139.9, 139.6, 137.3, 137.0, 130.2, 129.8, 128.0, 127.9, 127.9, 127.8, 127.5, 127.3, 127.2, 127.1, 126.8, 126.5, 118.2, 118.1, 57.3, 56.5, 54.9, 54.5, 19.4, 18.8; HRMS (EI) *m*/*z* 266

(M^+), 117 (100), 91, 70, 45; HRMS (EI) calcd for $C_{18}H_{18}O_2$ (M^+) 266.1307, found 266.1283.

*4.4.40. (E)-4-Acetoxybut-2-enyl 2-bromo-2-methylpropanoate (E-**45**).* A colorless oil; IR (neat), ν_{max} 2978, 1748, 1463, 1372, 1275, 1166, 1111, 1028, 969, 642, 475 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.90 (dt, *J* 4.4 Hz, 2H), 4.69 (d, *J* 4.1 Hz, 2H), 4.60 (d, *J* 4.1 Hz, 2H), 1.97 (s, 3H), 1.95 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.2, 170.5, 128.1, 127.1, 65.0, 63.7, 55.4, 30.6, 20.7; MS(EI) *m*/*z* 278 (M^+); HRMS (EI) calcd for $C_{11}H_{17}{}^{79}BrO_3$ (M^+) 278.0154, found 278.0156.

*4.4.41. 3-(Acetoxymethyl)-2,2-dimethylpent-4-enoic acid (**46**).* IR (neat), ν_{max} 3200 (br), 2981, 1744, 1467, 1367, 1243, 1162, 1039, 929, 686, 606 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.64 (dt, *J* 16.8, 10.4 Hz, 1H), 5.21 (dd, *J* 10.4, 1.6 Hz, 1H), 5.19 (dd, *J* 16.8, 0.6 Hz, 1H), 4.20–4.03 (m, 2H), 2.80 (d, *J* 8.0 Hz, 1H), 2.75 (d, *J* 8.0 Hz, 1H), 2.00 (s, 3H), 1.17 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 183.4, 170.8, 134.0, 119.7, 63.9, 49.7, 43.2, 24.4, 20.2; MS (EI) *m*/*z* 200 (M^+); HRMS (EI) calcd for $C_{10}H_{16}O_4$ (M^+) 200.1048, found 200.1027.

*4.4.42. (E)-4-Acetoxybut-2-enyl 2-bromopropanoate (**47**).* A pale yellow oil; IR (neat), ν_{max} 2941, 1740, 447, 1380, 1336, 1229, 1159, 1028, 975, 638 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.97–5.83 (m, 2H), 4.68 (dd, *J* 3.8 Hz, 2H), 4.59 (d, *J* 4.1 Hz, 2H), 4.39 (q, *J* 7.1 Hz, 1H), 2.09 (s, 3H), 1.85 (d, *J* 7.1 Hz, 3H); MS (EI) *m*/*z* 43 (100), 70, 112, 135, 152, 264 ($M-H^+$); HRMS (EI) calcd for $C_9H_{13}{}^{81}BrO_4$ (M^+) 265.9977, found 265.9966.

*4.4.43. 3-(Acetoxymethyl)-2-methylpent-4-enoic acid (**48**).* A white crystal; IR (neat), ν_{max} 3082, 2979, 1741, 1460, 1383, 1250, 1042, 999, 927, 680 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.79–5.70 (m, 0.24×1H), 5.65–5.56 (m, 0.76×1H), 5.20–5.14 (m, 2H), 4.23–4.13 (m, 2H), 2.79–2.75 (m, 0.24×1H), 2.73–2.65 (m, 0.76×2H), 2.63–2.58 (m, 0.24×1H), 2.04 (s, 3H), 1.19 (d, *J* 6.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 185.6, 181.4, 180.7, 170.9, 135.4, 134.7, 119.0, 118.4, 65.2, 64.4, 45.3, 45.2, 40.4, 40.3, 14.0, 13.8, 13.8; MS (EI) *m*/*z* 187 ($M+1^+$); HRMS (EI) calcd for $C_9H_{14}O_4$ (M^+) 186.0892, found 186.0880.

*4.4.44. (E)-4-Acetoxy-3-methylbut-2-enyl 2-bromo-2-methylpropan oate (**49**).* A pale yellow oil; IR (neat), ν_{max} 2930, 1739, 1460, 1374, 1231, 1161, 1110, 1027, 962, 645, 476 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.64 (t, *J* 6.8 Hz, 1H), 4.73 (d, *J* 6.9 Hz, 2H), 4.51 (s, 2H), 2.10 (s, 3H), 1.94 (s, 6H), 1.76 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.3, 170.7, 136.5, 120.8, 68.4, 62.1, 55.7, 30.7, 20.8, 14.2; MS (EI) *m*/*z* 292 ($M+H^+$); HRMS (EI) calcd for $C_{11}H_{17}{}^{79}BrO_4$ (M^+) 292.0310, found 292.0304.

*4.4.45. 3-(Acetoxymethyl)-2,2,3-trimethylpent-4-enoic acid (**50**).* A yellow oil; IR (neat), ν_{max} 2984, 1742, 1471, 1417, 1385, 1242, 1037, 921, 606, 452, 440 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.90 (dd, *J* 17.4, 10.9 Hz, 1H), 5.20 (dd, *J* 10.9, 0.8 Hz, 1H), 5.08 (dd, *J* 17.3, 0.8 Hz, 1H), 4.26 (d, *J* 11.1 Hz, 1H), 4.13 (d, *J* 11.1 Hz, 1H), 2.02 (s, 3H), 1.20 (s, 3H), 1.19 (s, 3H), 1.16 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 182.8, 171.0, 139.5, 115.7, 68.1, 46.8, 44.4, 21.6, 20.8, 16.7; MS (EI) *m*/*z* 214 (M^+); HRMS (EI) calcd for $C_{11}H_{18}O_4$ (M^+) 214.1205, found 214.1197.

*4.4.46. 3-(Methoxycarbonyl)-2,2-dimethylpent-4-enoic acid (**52**).* A colorless oil; IR (neat), ν_{max} 2987, 1715, 1368, 1474, 1437, 1268, 1027, 932 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.88 (dt, *J* 17.1, 9.8 Hz, 1H), 5.29 (d, *J* 10.2 Hz, 1H), 5.22 (d, *J* 17.1 Hz, 1H), 3.69 (s, 3H), 3.42 (d, *J* 6.8 Hz, 2H), 1.26 (s, 3H), 1.23 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.5, 23.8, 44.4, 51.8, 56.8, 120.7, 131.7, 172.4, 182.6; MS (EI) *m*/*z* 187 (M+1), 189, 155, 127, 99 (100); HRMS (EI) calcd for $C_9H_{14}O_4$ (M^+), 186.0892, found 186.0875.

*4.4.47. (Z)-Methyl 4-(isobutyryloxy)but-3-enoate (**54**).* A colorless oil; IR (neat), ν_{max} 2982, 1766, 1676, 1472, 1268, 1018, 853, 748, 593 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.19 (d, *J* 6.3 Hz, 1H), 5.12 (dt, *J* 6.3, 6.8 Hz, 1H), 3.71 (s, 3H), 3.23 (d, *J* 6.8 Hz, 2H), 2.65 (quint, *J* 6.8 Hz, 1H), 1.22 (d, *J* 6.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.5, 171.1, 136.1, 105.0, 65.8, 33.8, 30.0, 15.2, 14.1; MS (EI) *m*/*z* 186 (M^+), 84, 71 (100); HRMS (EI) calcd for $C_9H_{14}O_4$ (M^+), 186.0892, found 186.0869.

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Supplementary data

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