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Zinc(II) oxide: an efficient catalyst for selective transesterification of β-ketoesters

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ABSTRACT

A facile and selective transesterification of β-ketoesters using zinc(II) oxide as catalyst is described. The emphasis has been placed on the reaction of methyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate with a series of alcohols of different structures, leading in all cases good to excellent yields.

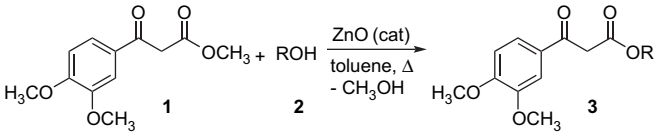
1. Introduction

β-Ketoesters are some of the most important building blocks in organic synthesis. The reactivity of this class of compounds allows for their rapid elaboration into more complex molecular structures. A key factor in the chemistry of β-ketoesters is their ability to serve as both nucleophilic and an electrophilic reagents. Our group in particular has dedicated a considerable effort to the study of the nucleophilic reactions of these substrates at the intercarbonylic position.[1] Thus, we have described diastereoselective alkylation of chiral derivatives of different acetoacetic acids and their transformation to enantiomerically pure 4,4-disubstituted 2-pyrazolin-5-ones[2] and to the synthesis of quaternary α-amino acids.[3] Moreover, we demonstrated that Ni(salicylaldehydate)$_2$,[4] Cu(5-*tert*-butylsalicylaldehydate)$_2$,[5] tributylphosphine,[6] and Eu-containing organic gels[7] are effective catalysts for conjugate additions, with high enantioselectivities obtained in Michael additions of cyclic β-ketoesters in the presence of lanthanum triflates and (*S*,*S*)-ip-pybox.[8]

A classic method for the preparation of β-ketoesters is the reaction of diketene with alcohols.[9] In 1995, we demonstrated that 2,2,6-trimethyl-4*H*-1,3-dioxin-4-one (diketene acetone adduct) is a superior alternative to the use of diketone.[10] However, for the preparation of structurally general β-ketoesters acylation of Meldrum's acid and subsequent reaction with alcohols should be used.[11]

Transesterification reaction represents the electrophilic facet of the reactivity of β-ketoesters. Most of the methods of transesterification are equilibrium driven reactions where the excess of one of the reactants is required to achieve good yields. This equilibrium process can be catalyzed by a wide range of catalysts, including the recently described catalysis by zeolites[12] and natural clays,[13] Mg-Al-hydrotalcites-like anionic clays,[14] montmorillonite K-10,[15] Nb_2O_5,[16] polyaniline salts,[17] B_2O_3/ZrO_2,[18] Zn,[19] NH_2SO_3H/[C_3MIm]Cl.[20]

During our work on the synthesis of biologically active compounds one of the steps required preparation of a series of analogs of 3-(3,4-dimethoxyphenyl)-3-oxopropanoate, **1**, varying only the alcohol part of the ester group. We, therefore, needed to identify an efficient protocol for the transesterification of **1** that would be suitable for a wide range of alcohols. Preliminary experiments were carried out using a catalytic amount of Zn dust[19a] in refluxing toluene and only moderate reaction yields were obtained (**3f** (52%) and **5f** (56%)). After some experimentation, we found that this reaction could be efficiently mediated by catalytic amounts of ZnO (Scheme 1).



Scheme 1. Synthesis of β-ketoester derivatives via transesterification of **1**.

2. Results and discussion

In order to establish the efficacy of ZnO as a catalyst, we investigated the transesterification of methyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate, **1**, using a range of alcohols in the presence of 20% ZnO in refluxing toluene. As can be seen in Table 1, smooth transesterification of **1** took place with a variety of alcohols, affording β-ketoester products **3a–j** in good to excellent yields. With the exception of entries 2 and 5, all reactions were carried out in 24 h or less. Results were particularly good in the case of primary (entry 1) and secondary (entries 2–4) alcohols, with the reaction reaching completion in as little as 1–6 h. Interestingly, the longest reaction time, 48 h, was required for the transesterification of **1** with isopropanol, the most volatile of series (entry 2). A likely explanation for this phenomenon is the lower concentration of the volatile alcohols in solution. The trend seems to hold true for tertiary alcohols, with the yield varying according to the boiling point.

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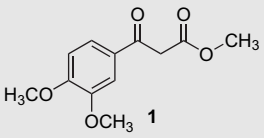
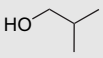
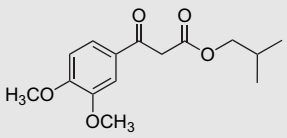
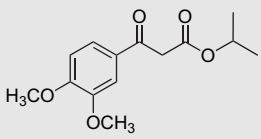
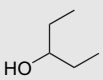
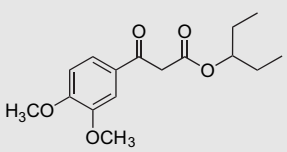
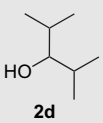
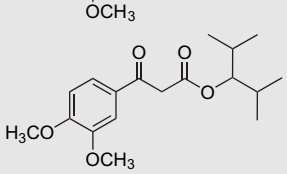
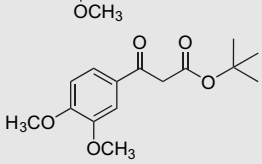
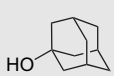
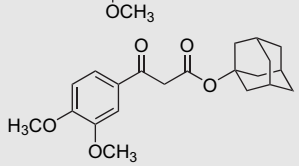
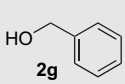
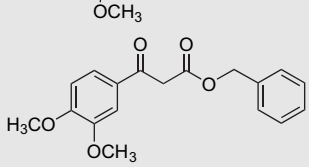
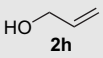
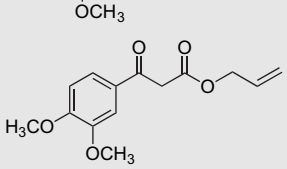
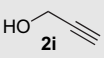
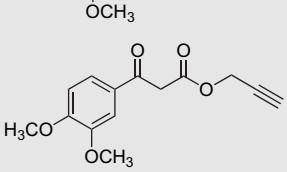
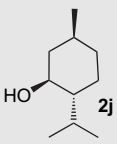
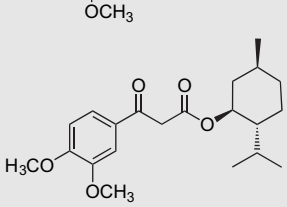
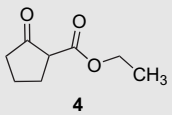
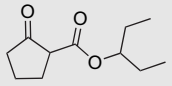
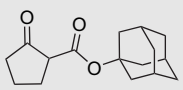
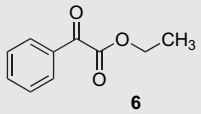
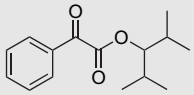
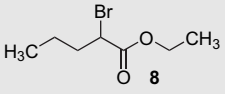
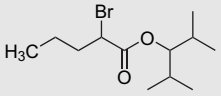
Table 1
Transesterification of β-ketoesters catalyzed by ZnO[a]

Entry	β-Ketoester	Alcohol	Product	Product number	Time (h)	Yield[b] (%)
1	 **1**	 **2a**		**3a**	5	93
2	**1**	 **2b**		**3b**	48	93
3	**1**	 **2c**		**3c**	6	99
4	**1**	 **2d**		**3d**	1	96
5	**1**	 **2e**		**3e**	72	62
6	**1**	 **2f**		**3f**	24	87[c]
7	**1**	 **2g**		**3g**	2	82
8	**1**	 **2h**		**3h**	3.5	90
9	**1**	 **2i**		**3i**	5	81
10	**1**	 **2j**		**3j**	1	99 (92)[d]
11	 **4**	**2c**		**5c**	2	98
12	**4**	**2f**		**5f**	5	83

(*continued on next page*)

Table 1 (*continued*)

Entry	β-Ketoester	Alcohol	Product	Product number	Time (h)	Yield[b] (%)
13	 **6**	**2d**		**7d**	24	—[e]
14	 **8**	**2d**		**9d**	24	—[e]

[a] Reaction conducted using 10 equiv of ROH and 20% ZnO in toluene at reflux.
[b] Yields correspond to the isolated product.
[c] Using 1.3 equiv of ROH.
[d] Using 1.5 equiv of menthol.
[e] No reaction took place.

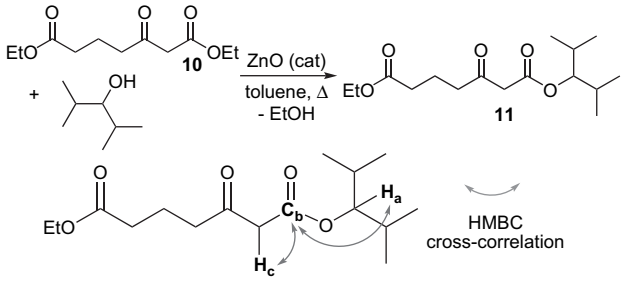
Thus, while a moderate 62% yield was achieved for *tert*-butanol (bp=83 °C) after 72 h (**3e**, entry 5), the less volatile 1-adamantanol (sublimes at >200 °C) afforded 87% of the transesterification product **3f** (entry 6) after just 24 h. As demonstrated in entries 7–9, the protocol was not limited to the regular aliphatic alcohols, and gave good yields even with the less nucleophilic benzylic, allylic, and propargylic alcohols. It should be noted that the resulting allyl and propargylic esters can be difficult to prepare as they readily undergo the Carroll rearrangement (successive decarboxylation and rearrangement) to give unsaturated ketones.[21]

Menthol, a chiral sterically hindered secondary alcohol, underwent transesterification giving the desired **3j** in a 99% yield (entry 10). While 10 equiv of menthol was used to assure complete conversion, the reaction was shown to take place even with 1.5 equiv of the alcohol, leading to yields only slightly inferior to those with 10 equiv. The protocol, therefore, should be suitable even for cases where the use of a large excess of the alcohol is undesirable due to the high price of this reagent.

It should be noted that while this work focused mainly on the synthesis of derivatives of **1**, the method is applicable to the transesterification of other β-ketoesters. Some examples include the synthesis of cyclic derivatives, where products **5c** and **5f** (entries 11 and 12) were obtained in 98 and 83% yield, respectively (entries 11 and 12).

It is important to mention that the reaction appears to be specific for the transesterification of β-ketoesters. Other ester derivatives, such as α-ketoesters as well as normal esters failed to undergo the reaction (entries 13 and 14). This difference in reactivity offered the possibility to perform the transesterification in a chemoselective fashion. This was demonstrated using substrate **10** that contains both a β-ketoester and an isolated ethyl ester groups. Indeed, submitting **10** to the reaction in the presence of ZnO and a large excess of 2,4-dimethylpentan-3-ol resulted in the formation of the singly-substituted product **11** in 92% yield (Scheme 2). The chemoselectivity of the reaction was established unequivocally by obtaining a two-dimensional HMBC NMR spectrum of **11**. Based on the presence of cross-peaks between the ^{13}C resonance of carbonyl C_b (167 ppm) and the ^{1}H resonances of both the methine H_a (4.59 ppm) and the intercarbonylic H_b (3.44 ppm), it was confirmed that the substitution took place selectively at the β-dicarbonyl moiety.

In summary, we report a new and highly efficient procedure for the transesterification of β-ketoesters using ZnO as catalyst with several kinds of alcohols leading good to excellent yields. The advantages of the catalyst are its easy and simple operation in the workup, its selectivity, its generality, and its lower cost of acquisition. We believe that this will present a better and more economical alternative to the existing methodologies and will find widespread application in industries as well as in organic synthesis.



Scheme 2. Selective transesterification of substrate **10** and summary of the results of the HMBC spectrum of product **11**.

3. Experimental section

3.1. General comments

All solvents were dried by standard methods. For ^{1}H and ^{13}C NMR spectra the deuterated solvents indicated were used. For preparative scale chromatography, silica gel (60–200 mesh) was used. Melting points are uncorrected.

3.1.1. *Methyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**1**)*

The preparation of β-diketone **1** was adapted from a procedure reported by Morrison.[22] To a 250 mL round-bottom flask containing dimethyl carbonate (7.0 mL, 83 mmol), NaH (2.23 g, 55.8 mmol, 60% suspension in Nujol) and THF (50 mL) was added dropwise a solution of 3,4-dimethoxyacetophenone (5.00 g, 27.8 mmol) in THF (40 mL). The reaction mixture was heated to reflux for 5 h, at which point TLC showed complete consumption of the starting ketone. The contents of the flask were poured into water, the pH adjusted to 9, and the mixture was extracted with CH_2Cl_2. The organic phase was dried with anhydrous Na_2SO_4 and the solvent was removed. The resulting crude product was purified by column chromatography on silica gel, eluting with hexane/ethyl acetate (5:1) mixture, giving 6.40 g of a white solid identified as **1** (26.9 mmol, 97%). R_f (2:1 hexane/ethyl acetate)=0.46. ^{1}H NMR ($CDCl_3$, 360 MHz): keto (95%)–enol (5%), 3.67 (s, 2.85H, OCO–CH_3), 3.70 (s, enol, 0.15H, OCO–CH_3), 3.89 (s, 3H, OCH_3), 3.91 (s, 3H, OCH_3), 3.93 (s, 1.90H, CO–CH_2), 5.56 (s, enol, 0.05H, C=CH), 6.85 (d, J=8.5 Hz, enol, 0.05H, $H_{aromatic}$), 6.86 (d, J=8.3 Hz, 0.95H, $H_{aromatic}$), 7.35 (dd, J=2.1, 8.5 Hz, enol, 0.05H, $H_{aromatic}$), 7.48 (d, J=2.1 Hz, 0.95H, $H_{aromatic}$), 7.51 (dd, J=2.1, 8.3 Hz, 0.95H, $H_{aromatic}$), 12.54 (s, enol, 0.05H, OH). ^{13}C NMR ($CDCl_3$, 90 MHz): 45.6 (CO–CH_2), 51.6 (*enol*, OCO–CH_3), 52.7 (OCO–CH_3), 56.2 (OCH_3), 56.3 (OCH_3), 56.5 (*enol*, OCH_3), 56.6 (*enol*, OCH_3), 85.9 (*enol*, C=CH), 109.0 (*enol*, $C_{aromatic}$), 110.3 ($C_{aromatic}$), 110.5 ($C_{aromatic}$), 110.9 (*enol*, $C_{aromatic}$), 119.8 (*enol*, $C_{aromatic}$), 123.8 ($C_{aromatic}$), 126.1 (*enol*, $C_{aromatic}$), 129.4 ($C_{aromatic}$), 149.4 ($C_{aromatic}$), 154.1 ($C_{aromatic}$), 168.4 (O–C=O), 191.1 (C=O). IR (ATR, ν cm^{-1}): 3068

(ArC–H st), 2980 (C–H st), 2949 (C–H st), 2839 (C–H st), 1732 (C=O st), 1667 (C=O st), 1583 (ArC–C), 1510 (ArC–C), 1419 (CH_3 δ as.), 1256 (C–O–C st as), 1243 (C–O–C st as), 1146 (C–O–C st as), 1018 (C–O–C st as).

3.1.2. General procedure for the transesterification process: preparation of isobutyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3a**)

A round-bottom flask was charged with 3-(3,4-dimethoxyphenyl)-3-oxopropanoate **1** (2.00 g, 8.39 mmol), 2-methylpropan-1-ol (7.75 mL, 83 mmol), ZnO (0.136 g, 1.67 mmol) and 10 mL of toluene. The flask was fitted with a short-path distillation head and heated, distilling the methanol formed during the reaction. After 5 h the TLC of the reaction mixture showed complete consumption of the β-ketoester. The reaction mixture was filtered through a plug of Celite to remove the catalyst. The filtrate was concentrated under reduced pressure and the crude residue was purified by column chromatography on silica gel, eluting with a mixture of *n*-hexane/ethyl acetate (3:1), affording 2.29 g (93%) of the product as colorless oil. R_f (2:1 hexane/ethyl acetate)=0.53. ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (94%)–enol (6%), 0.86 (d, *J*=6.8 Hz, 5.64H, CHC*H*$_3$), 0.96 (d, *J*=6.8 Hz, 0.36H, enol, CHC*H*$_3$), 1.90 (sept, *J*=6.6 Hz, 1H, C*H*CH$_3$), 3.90 (d, *J*=6.6 Hz, 2H, OC*H*CH), 3.91 (s, 3H, OC*H*$_3$), 3.93 (s, 3H, OC*H*$_3$), 3.94 (s, 2H, CO–C*H*$_2$), 5.59 (s, 0.06H, enol, C=C*H*), 6.88 (d, *J*=8.1 Hz, 1H, $H_{aromatic}$), 7.29 (d, *J*=2.4 Hz, 0.06H, enol, $H_{aromatic}$), 7.39 (dd, *J*=8.2, 2.4 Hz, 0.06H, enol, $H_{aromatic}$), 7.51–7.55 (m, 1.88H, $H_{aromatic}$), 12.71 (s, 0.06H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 19.2 (CH*C*H$_3$), 19.4 (*enol*, CH*C*H$_3$), 27.2 (*C*HCH$_3$), 46.0 (CO–*C*H$_2$), 56.3 (OCH$_3$), 56.4 (OCH$_3$), 70.3 (*enol*, OCHCH), 71.8 (OCHCH), 86.2 (*enol*, C=*C*H), 110.3 (*C*H$_{aromatic}$), 110.7 (*C*H$_{aromatic}$), 111.0 (*enol*, *C*H$_{aromatic}$), 123.8 (*C*H$_{aromatic}$), 129.6 (*C*H$_{aromatic}$), 149.5 (*C*$_{aromatic}$), 154.1 (*C*$_{aromatic}$), 168.0 (O–C=O), 191.3 (C=O). IR (ATR, ν cm^{-1}):2959 (C–H st), 2874 (C–H st), 2839 (C–H st), 1733 (C=O st), 1673 (C=O st), 1584 (ArC–C), 1513 (ArC–C), 1417 (CH_3 δ as.), 1256 (C–O–C st as), 1147 (C–O–C st as), 1103 (C–O–C st as), 1019 (C–O–C st sim). Anal. Calcd for $C_{15}H_{20}O_5$: C, 64.27; H, 7.19. Found: C, 64.37; H, 7.29.

3.1.3. Isopropyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3b**)

Following the general procedure, β-ketoester **1** (10.19 g, 42.7 mmol) was allowed to react with isopropanol (77 mL, 427 mmol, 10 equiv) in the presence of ZnO (0.69 g, 8.55 mmol, 20 mol %) and 10 mL of toluene for 48 h. Column chromatography: silica gel, hexane/ethyl acetate (3:1). R_f (2:1 hexane/ethyl acetate)=0.53. Colorless oil; yield: 10.59 g (39.8 mmol, 93%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (94%)–enol (6%), 1.21 (d, *J*=6.12 Hz, 5.64H, CHC*H*$_3$), 1.28 (d, *J*=6.1 Hz, 0.36H, enol, CHC*H*$_3$), 3.89 (s, 1.88H, CO–C*H*$_2$), 3.91 (d, *J*=7.6 Hz, 6H, OCH$_3$), 5.04 (sept, *J*=6.5 Hz, 0.94H, OC*H*CH$_3$), 5.13 (m, 0.06H, enol, OC*H*CH$_3$), 5.54 (s, 0.06H, enol, C=C*H*), 6.87 (d, *J*=8.2 Hz, 1H, $H_{aromatic}$), 7.29 (d, *J*=2.4 Hz, 0.06H, enol, $H_{aromatic}$), 7.37 (dd, *J*=8.2, 1.8 Hz, 0.06H, enol, $H_{aromatic}$), 7.50–7.54 (m, 1.88H, $H_{aromatic}$), 12.71 (s, 0.06H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 22.3 (CHC*H*$_3$), 22.6 (*enol*, CHC*H*$_3$), 46.7 (CH$_2$), 56.6 (OCH$_3$), 56.7 (OCH$_3$), 68.2 (*enol*, *C*HCH$_3$), 69.6 (*C*HCH$_3$), 87.1 (*enol*, C=*C*H), 109.3 (*enol*, *C*H$_{aromatic}$), 110.6 (*C*H$_{aromatic}$), 110.9 (*C*H$_{aromatic}$), 111.3 (*enol*, *C*H$_{aromatic}$), 120.1 (*enol*, *C*H$_{aromatic}$), 124.1 (*C*H$_{aromatic}$), 129.9 (*C*H$_{aromatic}$), 149.8 (*C*$_{aromatic}$), 154.4 (*C*$_{aromatic}$), 167.9 (O–C=O), 191.8 (C=O). IR (ATR, ν cm^{-1}): 3081 (ArC–H st), 2979 (C–H st), 2936 (C–H st), 2839 (C–H st), 1730 (C=O st), 1672 (C=O st), 1584 (ArC–C), 1513 (ArC–C), 1417 (CH_3 δ as.), 1256 (C–O–C st as), 1145 (C–O–C st as), 1103 (C–O–C st as), 1019 (C–O–C st).

3.1.4. Pentan-3-yl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3c**)

Following the general procedure, β-ketoester **1** (4.21 g, 17.7 mmol) was allowed to react with 3-pentanol (20 mL, 177 mmol, 10 equiv) in the presence of ZnO (0.27 g, 3.35 mmol, 19 mol %) and 5 mL of toluene for 6 h. Column chromatography: silica gel, hexane/ethyl acetate (3:1). R_f (2:1 hexane/ethyl acetate)=0.56. Colorless oil; yield: 5.14 g (17.4 mmol, 99%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (94%)–enol (6%), 0.83 (t, *J*=7.5 Hz, 5.64H, CH$_2$C*H*$_3$), 0.91 (t, *J*=7.5 Hz, 0.36H, enol, CH$_2$C*H*$_3$), 1.50–1.58 (m, 3.76H, C*H*$_2$CH$_3$), 1.59–1.64 (m, 0.24H, enol, C*H*$_2$CH$_3$), 3.91 (s, 2H, CO–C*H*$_2$), 3.92 (d, *J*=7.6 Hz, 6H, OC*H*$_3$), 4.80 (quint, *J*=6.6 Hz, 0.94H, OC*H*CH$_2$), 4.88 (quint, *J*=6.5 Hz, 0.06H, enol, OC*H*CH$_2$), 5.58 (s, 0.06H, enol, C=C*H*), 6.87 (d, *J*=8.3 Hz, 1H, $H_{aromatic}$), 7.29 (d, *J*=2.4 Hz, 0.06H, enol, $H_{aromatic}$), 7.39 (dd, *J*=8.5, 2.0 Hz, 0.06H, enol, $H_{aromatic}$), 7.52–7.56 (m, 1.88H, $H_{aromatic}$), 12.74 (s, 0.06H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 9.8 (CH$_2$*C*H$_3$), 10.0 (*enol*, CH$_2$*C*H$_3$), 26.6 (*C*H$_2$CH$_3$), 26.9 (*enol*, *C*H$_2$CH$_3$), 46.4 (CO–*C*H$_2$), 56.3 (OCH$_3$), 56.4 (OCH$_3$), 78.4 (CO–*C*H$_2$), 86.6 (*enol*, C=*C*H), 109.0 (*enol*, *C*H$_{aromatic}$), 110.34 (*C*H$_{aromatic}$), 110.6 (*C*H$_{aromatic}$), 123.8 (*C*H$_{aromatic}$), 129.7 (*C*H$_{aromatic}$), 149.5 (*C*$_{aromatic}$), 154.0 (*C*$_{aromatic}$), 167.9 (O–C=O), 191.5 (C=O). IR (ATR, ν cm^{-1}): 3080 (ArC–H st), 2967 (C–H st), 2936 (C–H st), 2878 (C–H st), 2839 (C–H st), 1729 (C=O st), 1673 (C=O st), 1585 (ArC–C), 1513 (ArC–C), 1417 (CH_3 δ as.), 1317 (C–O–C st as), 1255 (C–O–C st as), 1148 (C–O–C st as), 1130 (C–O–C st as), 1020 (C–O–C st). Anal. Calcd for $C_{16}H_{22}O_5$: C, 65.29; H, 7.53. Found: C, 65.39; H, 7.73.

3.1.5. 2,4-Dimethylpentan-3-yl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3d**)

Following the general procedure, β-ketoester **1** (1.00 g, 4.19 mmol) was allowed to react with 2,4-dimethylpentan-3-ol (5.88 mL, 41.9 mmol, 10 equiv) in the presence of ZnO (0.07 g, 0.84 mmol, 20 mol %) and 5 mL of toluene for 1 h. Column chromatography: silica gel, hexane/ethyl acetate (4:1). R_f (2:1 hexane/ethyl acetate)=0.6. Colorless oil; yield: 1.32 g (4.09 mmol, 96%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (94%)–enol (6%), 0.81 (d, *J*=6.7 Hz, 5.64H, CHC*H*$_3$), 0.84 (d, *J*=6.7 Hz, 5.64H, CHC*H*$_3$), 0.90 (d, *J*=3.8 Hz, 0.36H, enol, CHC*H*$_3$), 0.91 (d, *J*=3.8 Hz, 0.36H, enol, CHC*H*$_3$), 1.86 (oct, *J*=6.5 Hz, 1.88H, C*H*CH$_3$), 1.91–1.99 (m, 0.12H, enol, C*H*CH$_3$), 3.92 (s, 3H, OC*H*$_3$), 3.94 (s, 3H, OC*H*$_3$), 3.97 (s, 1.94H, CO–C*H*$_2$), 4.62 (t, *J*=6.1 Hz, 1.94H, C*H*CH), 4.71 (t, *J*=6.2 Hz, 0.06H, enol, C*H*CH), 5.60 (s, 0.06H, enol, C=C*H*), 6.88 (d, *J*=8.5 Hz, 1H, $H_{aromatic}$), 7.30 (d, *J*=2.1 Hz, 0.06H, enol, $H_{aromatic}$), 7.41 (dd, *J*=8.5, 2.0 Hz, 0.06H, enol, $H_{aromatic}$), 7.53 (d, *J*=2.1 Hz, 0.94H, $H_{aromatic}$), 7.57 (dd, *J*=8.5, 2.0 Hz, 0.94H, $H_{aromatic}$), 12.76 (s, 0.06H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 17.4 (CH*C*H$_3$), 17.5 (*enol*, CHC*H*$_3$), 19.8 (CH*C*H$_3$), 19.9 (*enol*, CH*C*H$_3$), 29.7 (*C*HCH$_3$), 29.8 (*enol*, *C*HCH$_3$), 46.2 (CO–*C*H$_2$), 56.3 (OCH$_3$), 56.4 (OCH$_3$), 82.8 (*enol*, CO–*C*H$_2$), 85.0 (CO–*C*H$_2$), 86.3 (*enol*, C=*C*H), 110.4 (*C*H$_{aromatic}$), 110.7 (*C*H$_{aromatic}$), 120.0 enol (*C*H$_{aromatic}$), 124.0 (*C*H$_{aromatic}$), 130.0 (*C*H$_{aromatic}$), 149.5 (*C*$_{aromatic}$), 154.1 (*C*$_{aromatic}$), 168.0 (O–C=O), 191.4 (C=O). IR (ATR, ν cm^{-1}): 3082 (ArC–H st), 2963 (C–H st), 2935 (C–H st), 2839 (C–H st), 1729 (C=O st), 1674 (C=O st), 1585 (ArC–C), 1513 (ArC–C), 1417 (CH_3 δ as.), 1322 (CH_3 δ as.), 1255 (CH_3 δ as.), 1128 (CH_3 δ as.), 1021 (CH_3 δ). Anal. Calcd for $C_{18}H_{26}O_5$: C, 67.06; H, 8.13. Found: C, 67.02; H, 8.43.

3.1.6. tert-Butyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3e**)

Following the general procedure, β-ketoester **1** (2.00 g, 8.39 mmol) was allowed to react with *tert*-butanol (8 mL, 83 mmol, 10 equiv) in the presence of ZnO (0.14 g, 1.67 mmol, 20 mol %) and 5 mL of toluene for 72 h. Column chromatography: silica gel, hexane/ethyl acetate (3:1). R_f (2:1 hexane/ethyl acetate)=0.57. Colorless oil; yield: 1.45 g (5.2 mmol, 62%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (94%)–enol (6%), 1.41 (s, 8.46H, CC*H*$_3$), 1.51 (s, 0.54H, enol, CC*H*$_3$), 3.83 (s, 1.88H, CO–C*H*$_2$), 3.90 (s, 3H, OC*H*$_3$), 3.92 (s, 3H, OC*H*$_3$), 5.48 (s, 0.06H, enol, C=C*H*), 6.87 (d, *J*=8.3 Hz, 1H, $H_{aromatic}$), 7.30 (d, *J*=2.4 Hz, 0.06H, enol, $H_{aromatic}$), 7.35 (dd, *J*=8.4, 2.3 Hz, 0.06H, enol, $H_{aromatic}$), 7.50–7.53 (m, 1.88H, $H_{aromatic}$), 12.71 (s, 0.06H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 28.2 (C*C*H$_3$), 28.7 (*enol*, C*C*H$_3$), 47.4 (CO–*C*H$_2$), 56.2 (OCH$_3$), 56.4 (OCH$_3$), 81.3 (*enol*, O*C*CH$_3$), 82.2 (O*C*CH$_3$), 87.8 (*enol*, C=*C*H), 108.9 (*enol*, *C*H$_{aromatic}$), 110.3 (*C*H$_{aromatic}$), 110.6 (*C*H$_{aromatic}$), 110.9 (*enol*, *C*H$_{aromatic}$), 119.6 (*enol*, *C*H$_{aromatic}$), 123.7 (*C*H$_{aromatic}$), 129.8 (*C*H$_{aromatic}$), 149.4

($C_{aromatic}$), 153.9 ($C_{aromatic}$), 167.2 (O–C=O), 191.8 (C=O). IR (ATR, ν cm^{-1}): 2974 (C–H st), 2935 (C–H st), 2839 (C–H st), 1728 (C=O st), 1673 (C=O st), 1584 (ArC–C), 1513 (ArC–C), 1417 (CH_3 δ as.), 1256 (C–O–C st as), 1129 (C–O–C st as), 1020 (C–O–C st sim). Anal. Calcd for $C_{15}H_{20}O_5$: C, 64.27; H, 7.19. Found: C, 64.62; H, 7.21.

3.1.7. Adamantyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3f**)

Following the general procedure, β-ketoester **1** (18.9 g, 79.5 mmol) was allowed to react with 1-adamantanol (15.81 g, 103.7 mmol, 1.3 equiv) in the presence of ZnO (1.34 g, 16.6 mmol, 21 mol %) and 200 mL of toluene for 24 h. Column chromatography: silica gel, hexane/ethyl acetate (3:1). R_f (2:1 hexane/ethyl acetate)=0.58. Colorless oil, solidified to a white solid after 2 days under vacuum; yield: 24.7 g (68.9 mmol, 87%). Mp: 84–85 °C. ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (96%)–enol (4%), 1.62 (s, 6H, CH_2CHCH_2ada), 2.07 (d, J=2.9 Hz, 6H, CH_2CHCH_2ada), 2.13 (s, 3H, CH_2CHCH_2ada), 2.18 (s, 0.36H, enol, CH_2CHCH_2ada), 3.84 (s, 1.92H, CO–CH_2), 3.92 (s, 3H, OCH_3), 3.94 (s, 3H, OCH_3), 5.49 (s, enol, 0.04H, C=C*H*), 6.88 (d, J=8.3 Hz, 1H, $H_{aromatic}$), 7.30 (d, J=2.1 Hz, enol, 0.04H, $H_{aromatic}$), 7.37 (dd, J=2.1, 8.5 Hz, enol, 0.04H, $H_{aromatic}$), 7.51–7.55 (m, 1.92H, $H_{aromatic}$), 12.54 (s, 0.04H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 31.1 (*enol*, CH_2CHCH_2ada), 31.2 (CH_2CHCH_2ada), 36.4 (CH_2CHCH_2ada), 36.5 (*enol*, CH_2CHCH_2ada), 41.4 (CH_2CHCH_2ada), 41.9 (*enol*, CH_2CHCH_2ada), 47.6 ($COCH_2COOR$), 56.3 (OCH_3), 56.4 (OCH_3), 65.1 (*enol*, $COCH_2CH$), 81.3 (*enol*, $OCCH_3$), 82.3 ($OC(CH_2)_3$), 87.9 (*enol*, C=*C*H), 110.3 ($CH_{aromatic}$), 110.6 ($CH_{aromatic}$), 111.0 (*enol*, $CH_{aromatic}$), 123.8 ($CH_{aromatic}$), 129.8 ($CH_{aromatic}$), 149.4 ($C_{aromatic}$), 153.9 ($C_{aromatic}$), 166.9 (O–C=O), 191.8 (C=O). IR (ATR, ν cm^{-1}): 2908 (C–H st), 2850 (C–H st), 1728 (C=O st), 1673 (C=O st), 1585 (ArC–C), 1514 (ArC–C), 1254 (C–O–C st as), 1147 (C–O–C st as), 1053 (C–O–C st as), 1021 (C–O–C st as).

3.1.8. Benzyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3g**)

Following the general procedure, β-ketoester **1** (2.00 g, 8.39 mmol) was allowed to react with benzylalcohol (8.6 mL, 83 mmol, 10 equiv) in the presence of ZnO (0.136 g, 1.67 mmol, 20 mol %) and 8 mL of toluene for 2 h. Column chromatography: silica gel, hexane/ethyl acetate (4:1). R_f (2:1 hexane/ethyl acetate)=0.54. Colorless oil; yield: 2.7 g (6.9 mmol, 82%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (93%)–enol (7%), 3.99 (s, 1.86H, CO–CH_2), 5.17 (s, 1.86H, $COCH_2$Ph), 5.23 (s, 0.14H, enol, $COCH_2$Ph), 5.65 (s, 0.07H, enol, C=C*H*), 6.84 (d, J=8.5 Hz, 1H, $H_{aromatic}$), 7.30 (s, 5H, $COCH_2$*Ph*), 7.49–7.52 (m, 1.86H, $H_{aromatic}$), 12.71 (s, 0.07H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 46.0 (CO–CH_2), 56.2 (OCH_3), 56.4 (OCH_3), 66.3 (*enol*, $COCH_2$Ph), 67.4 ($COCH_2$Ph), 86.8 (*enol*, C=*C*H), 110.2 (*enol*, $CH_{aromatic}$), 110.3 ($CH_{aromatic}$), 110.6 ($CH_{aromatic}$), 110.9 (*enol*, $CH_{aromatic}$), 123.6 (*enol*, $CH_{aromatic}$), 123.8 ($CH_{aromatic}$), 128.5 ($COCH_2$*Ph*), 128.6 ($COCH_2$*Ph*), 128.9 ($COCH_2$*Ph*), 129.5 ($CH_{aromatic}$), 135.7 ($COCH_2$*Ph*), 149.5 ($C_{aromatic}$), 154.1 ($C_{aromatic}$), 167.8 (O–C=O), 191.1 (C=O). IR (ATR, ν cm^{-1}): 3003 (*aromatic* CH st), 2936 (CH st), 2838 (C–H st), 1736 (C=O), 1671 (C=O), 1584 (*aromatic* C–C), 1511 (*aromatic* C–C), 1416 (CH_3 δ as.), 1263 (C–O–C st as), 1131 (C–O–C st as), 1019 (C–O–C st sim).

3.1.9. Allyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3h**)

Following the general procedure, β-ketoester **1** (1.50 g, 6.3 mmol) was allowed to react with allylalcohol (4.30 mL, 63 mmol, 10 equiv) in the presence of ZnO (0.10 g, 1.26 mmol, 20 mol %) and 8 mL of toluene for 3.5 h. Column chromatography: silica gel, hexane/ethyl acetate (2:1). R_f (2:1 hexane/ethyl acetate)=0.52. Colorless oil; yield: 1.50 g (5.6 mmol, 90%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (94%)–enol (6%), 3.91 (s, 3H, OCH_3), 3.93 (s, 3H, OCH_3), 3.98 (s, 1.88H, CO–CH_2), 4.64 (dt, J=5.7, 1.42 Hz, 1.88H, $COCH_2CH$), 4.69 (dt, J=5.7, 1.42 Hz, 0.12H, enol, $COCH_2CH$), 5.21 (dq, J=1.3, 10.5 Hz, 1H, C=CH_{trans}H), 5.29 (dq, J=1.3, 17.2 Hz, 1H, C=CHH_{cis}), 5.62 (s, 0.06H, enol, C=C*H*), 5.83–5.93 (m, 1H, CH_2CH=CH_2), 6.88 (d, J=8.4 Hz, 1H, $H_{aromatic}$), 7.28 (d, J=8.4 Hz, 0.08H, enol, $H_{aromatic}$), 7.39 (dd, J=8.4, 2.3 Hz, 0.07H, enol, $H_{aromatic}$), 7.51–7.54 (m, 1.88H, $H_{aromatic}$), 12.54 (s, 0.06H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 45.8 (CO–CH_2), 56.2 (OCH_3), 56.4 (OCH_3), 65.1 (*enol*, $COCH_2CH$), 86.0 (*enol*, C=*C*H), 110.3 ($CH_{aromatic}$), 110.5 ($CH_{aromatic}$), 111.0 (*enol*, $CH_{aromatic}$), 118.7 (*enol*, CH=CH_2), 118.9 (CH=CH_2), 123.7 ($CH_{aromatic}$), 129.5 ($CH_{aromatic}$), 131.9 (*C*H=CH_2), 149.5 ($C_{aromatic}$), 154.1 ($C_{aromatic}$), 167.7 (O–C=O), 191.1 (C=O). IR (ATR, ν cm^{-1}): 3081 (=CH_2 st), 2936 (C–H st), 2839 (C–H st), 1736 (C=O st), 1671 (C=O st), 1584 (ArC–C), 1513 (ArC–C), 1417 (CH_3 δ as.), 1256 (C–O–C st as), 1130 (C–O–C st as), 1019 (C–O–C st sim). Anal. Calcd for $C_{14}H_{16}O_5$: C, 63.63; H, 6.10. Found: C, 63.55; H, 6.10.

3.1.10. Prop-2-ynyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3i**)

Following the general procedure, β-ketoester **1** (1.50 g, 6.3 mmol) was allowed to react with propargylic alcohol (83.66 mL, 63 mmol, 10 equiv) in the presence of ZnO (0.100 g, 1.26 mmol, 20 mol %) and 10 mL of toluene for 5 h. Column chromatography: silica gel, hexane/ethyl acetate (2:1). R_f (2:1 hexane/ethyl acetate)=0.52. Light-yellow oil; yield: 1.33 g (5.1 mmol, 81%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (92%)–enol (8%), 2.48 (t, J=2.5 Hz, 0.92H, C≡C*H*), 2.51 (t, J=2.5 Hz, 0.08H, enol, C≡C*H*), 3.92 (s, 3H, OCH_3), 3.94 (s, 3H, OCH_3), 4.01 (s, 1.84H, CO–CH_2), 4.74 (d, J=2.6 Hz, 1.84H, $COCH_2C$≡CH), 4.80 (d, J=2.6 Hz, 0.16H, enol, $COCH_2C$≡CH), 5.64 (s, 0.08H, enol, C=C*H*), 6.88 (d, J=8.4 Hz, 1H, $H_{aromatic}$), 7.28 (d, J=8.4 Hz, 0.08H, enol, $H_{aromatic}$), 7.39 (dd, J=8.4, 2.3 Hz, 0.08H, enol, $H_{aromatic}$), 7.50–7.53 (m, 1.84H, $H_{aromatic}$), 12.55 (s, 0.08H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 45.6 (CO–CH_2), 53.1 ($COCH_2C$≡CH), 56.3 (OCH_3), 56.5 (OCH_3), 75.4 ($COCH_2C$≡*C*H), 77.4 ($COCH_2C$≡CH), 86.5 (*enol*, C=*C*H), 109.1 (*enol*, $CH_{aromatic}$), 110.3 ($CH_{aromatic}$), 110.5 ($CH_{aromatic}$), 111.0 (*enol*, $CH_{aromatic}$), 120.0 (*enol*, $CH_{aromatic}$), 123.8 ($CH_{aromatic}$), 129.3 ($CH_{aromatic}$), 149.5 ($C_{aromatic}$), 154.3 ($C_{aromatic}$), 167.2 (O–C=O), 190.7 (C=O). IR (ATR, ν cm^{-1}): 3261 (≡CH st), 2938 (C–H st), 2840 (C–H st), 2129 (C≡C st), 1740 (C=O st), 1671 (C=O st), 1584 (ArC–C), 1513 (ArC–C), 1417 (CH_3 δ as.), 1256 (C–O–C st as), 1129 (C–O–C st as), 1103 (C–O–C st as), 1017 (C–O–C st sim). Anal. Calcd for $C_{14}H_{14}O_5$: C, 64.12; H, 5.38. Found: C, 64.15; H, 5.41.

3.1.11. (1S,2R,5S)-2-Isopropyl-5-methylcyclohexyl 3-(3,4-dimethoxyphenyl)-3-oxopropanoate (**3j**)

Following the general procedure, β-ketoester **1** (2.00 g, 8.39 mmol) was allowed to react with (−)-menthol (13.1 g, 83 mmol, 10 equiv) in the presence of ZnO (0.136 g, 1.67 mmol, 20 mol %) and 15 mL of toluene for 1 h. Column chromatography: silica gel, hexane/ethyl acetate (2:1). R_f (2:1 hexane/ethyl acetate)=0.61. Colorless oil; yield: 3.025 g (8.37 mmol, 99%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (93%)–enol (7%), 0.66 (d, J=7.1 Hz, 3H, CH_3CHCH_3), 0.79 (d, J=7.1 Hz, 3H, CH_3CHCH_3), 0.87 (d, J=6.5 Hz, 3H, $CHCH_3$), 0.77–1.06 (m, 3H), 1.32 (tt, J=11.2, 3.2 Hz, 1H, $CHCH(CH_3)_2$), 1.38–1.52 (m, 1H, $(CH_2)_2CHCH_3$), 1.59–1.76 (m, 3H), 1.99 (d apparent, J=11.2 Hz, 1H, $CHCH(CH_3)_2$), 3.91 (s, 3H, OCH_3), 3.92 (q, J=28.8, 14.7 Hz, 2H, CO–CH_2), 3.93 (s, 3H, OCH_3), 4.70 (dt, J=4.2, 10.7 Hz, 0.93H, $COCH$), 4.70 (dt, J=4.2, 10.7 Hz, 0.07H, enol, $COCH$), 5.56 (s, 0.07H, enol, C=C*H*), 6.87 (d, J=8.4 Hz, 1H, $H_{aromatic}$), 7.28 (d, J=2.2 Hz, 0.07H, enol, $H_{aromatic}$), 7.39 (dd, J=8.4, 2.2 Hz, 0.07H, enol, $H_{aromatic}$), 7.50–7.55 (m, 1.86H, $H_{aromatic}$), 12.74 (s, 0.07H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 16.3 (CH_3CHCH_3), 16.7 (*enol*, CH_3CHCH_3), 21.0 (CH_3CHCH_3), 22.2 ($CHCH_3$), 22.3 (*enol*, $CHCH_3$), 23.5 ($CHCH_2CH_2$), 23.8 (*enol*, $CHCH_2CH_2$), 26.2 ($CHCH(CH_3)_2$), 26.6 (*enol*, $CHCH(CH_3)_2$), 31.7 ($CHCH_3$), 34.4 ($CHCH_2CH_2$), 34.5 (*enol*, $CHCH_2CH_2$), 40.9 ($CHCH_2CH$), 41.4 (*enol*, $CHCH_2CH$), 46.6 (CO–CH_2), 47.1 ($CHCH(CH_3)_2$), 47.5 (*enol*, $CHCH(CH_3)_2$), 56.3 (OCH_3), 56.4 (OCH_3), 74.3 (*enol*, $COCH$), 75.8 ($COCH$), 86.6 (*enol*, C=*C*H), 109.0 (*enol*, $CH_{aromatic}$), 110.3 ($CH_{aromatic}$), 110.6 ($CH_{aromatic}$), 111.0 (*enol*, $CH_{aromatic}$), 119.8 (*enol*, $CH_{aromatic}$), 123.7 ($CH_{aromatic}$), 129.7 ($CH_{aromatic}$), 149.5 ($C_{aromatic}$),

154.0 ($C_{aromatic}$), 167.5 (O–C=O), 191.4 (C=O). IR (ATR, ν cm^{-1}): 2953 (C–H st), 2868 (C–H st), 1729 (C=O st), 1675 (C=O st), 1585 (ArC–C), 1514 (ArC–C), 1417 (CH_3 δ as.), 1256 (C–O–C st as), 1148 (C–O–C st as), 1022 (C–O–C st sim). Anal. Calcd for $C_{21}H_{30}O_5$: C, 69.59; H, 8.34. Found: C, 68.97; H, 8.24.

*3.1.12. Pentan-3-yl 2-oxocyclopentanecarboxylate (**5c**)*

Following the general procedure, β-ketoester **4** (5.00 g, 30.4 mmol) was allowed to react with 3-pentanol (32 mL, 304 mmol, 10 equiv) in the presence of ZnO (0.49 g, 6.08 mmol, 20 mol %) and 30 mL of toluene for 2 h. Column chromatography: silica gel, hexane/ethyl acetate (4:1). R_f (2:1 hexane/ethyl acetate)=0.63. Colorless oil; yield: 5.9 g (29.7 mmol, 98%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (98%)–enol (2%), 0.84 (t, J=7.5 Hz, 3H, CH_2CH_3), 0.88 (t, J=7.5 Hz, 3H, CH_2CH_3), 1.49–1.62 (abs complex, 4H, CH_2CH_3), 1.78–1.92 (abs complex, 1H, CH_2CH_2CH), 2.06–2.16 (abs complex, 1H, CH_2CH_2CH), 2.24–2.31 (abs complex, 4H, $CH_2CH_2CH_2CH$), 3.12 (t, J=8.8 Hz, 0.98H, COC*H*COOR), 4.77 (quint, J=6.2 Hz, 1H, OC*H*$(CH_2)_2$), 10.44 (s, 0.02H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 9.8 (CH_2CH_3), 9.9 (CH_2CH_3), 21.3 (CH_2CH_2CH), 26.8 (CH_2CH_3), 27.8 (CH_2CH_2CH), 38.3 ($CH_2CH_2CH_2CH$), 55.3 (COCHCOOR), 78.2 (OCH $(CH_2)_2$), 169.6 (O–C=O), 212.8 (C=O). IR (ATR, ν cm^{-1}): 2967 (C–H st), 2940 (C–H st), 2880 (C–H st), 1752 (C=O st), 1718 (C=O st), 1458 (CH_3 δ as.), 1252 (C–O–C st as), 1189 (C–O–C st as), 1103 (C–O–C st as).

*3.1.13. Adamantyl 2-oxocyclopentanecarboxylate (**5f**)*

Following the general procedure, β-ketoester **4** (2 g, 12.80 mmol) was allowed to react with 1-adamantanol (2.92 g, 38.36 mmol, 3 equiv) in the presence of ZnO (0.20 g, 2.56 mmol, 20 mol %) and 20 mL of toluene for 5 h. Column chromatography: silica gel, hexane/ethyl acetate (3:1). R_f (3:1 hexane/ethyl acetate)=0.60. Colorless oil; yield: 2.78 g (10.62 mmol, 83%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (99%)–enol (1%), 1.64 (s, 6H, CH_2ada), 1.76–1.89 (abs complex, 1H, CH_2CH_2CH), 2.04–2.12 (abs complex, 1H, CH_2CH_2CH), 2.10 (s, 6H, CH_2CHCH_2ada), 2.14 (s, 3H, CH_2CHCH_2ada), 2.20–2.28 (abs complex, 4H, $CH_2CH_2CH_2CH$), 3.02 (t, J=8.9 Hz, 0.99H, COC*H*COOR), 10.43 (s, 0.01H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 21.2 (CH_2CH_2CH), 27.8 ($CH_2CH_2CH_2CH$), 31.2 (CH_2CHCH_2ada), 36.4 (CH_2CHCH_2ada), 38.4 ($CH_2CH_2CH_2CH$), 41.5 (CH_2CHCH_2ada), 56.2 (COCHCOOR), 82.0 (OC $(CH_2)_3$), 168.7 (O–C=O), 213.2 (C=O). IR (ATR, ν cm^{-1}): 2909 (C–H st), 2850 (C–H st), 1750 (C=O st), 1716 (C=O st), 1454 (CH_3 δ as.), 1248 (C–O–C st as), 1186 (C–O–C st as), 1102 (C–O–C st as), 1051 (C–O–C st sim). Anal. Calcd for $C_{16}H_{22}O_3$: C, 73.25; H, 8.45. Found: C, 73.12; H, 8.74. Bp: 175 °C at 0.55 mbar.

*3.1.14. 1-(2,4-Dimethylpentan-3-yl) 7-ethyl 3-oxoheptanedioate (**11**)*

Following the general procedure, β-ketoester **10** (1.5 g, 6.51 mmol) was allowed to react with 2,4-dimethylpentan-3-ol (9.13 mL, 65.1 mmol, 10 equiv) in the presence of ZnO (0.10 g, 1.30 mmol, 20 mol %) and 4 mL of toluene for 2 h. Column chromatography: silica gel, hexane/ethyl acetate (4:1). R_f (2:1 hexane/ethyl acetate)=0.62. Colorless oil; yield: 1.78 g (5.92 mmol, 92%). ^{1}H NMR ($CDCl_3$, 360 MHz) δ: keto (92%)–enol (8%), 0.83 (d, J=6.8 Hz, 6H, $CHCH_3$), 0.86 (d, J=6.8 Hz, 6H, $CHCH_3$), 1.21 (t, J=7.45 Hz, 3H, CH_2CH_3), 1.80–1.92 (m, 4H, $CHCH_3$, $CH_2CH_2CH_2$), 2.22 (t, J=7.2 Hz, 0.16H, enol, $CH_2CH_2CH_2$), 2.30 (t, J=7.2 Hz, 1.84H, $CH_2CH_2CH_2$), 2.61 (t, J=7.2 Hz, 2H, $CH_2CH_2CH_2$), 3.46 (s, 2H, $COCH_2CO$), 4.08 (q, J=7.2 Hz, 2H, CH_2CH_3), 4.62 (t, J=6.1 Hz, 1H, CHCH), 5.00 (s, 0.08H, enol, C=CH), 12.15 (s, 0.08H, enol, OH). ^{13}C NMR ($CDCl_3$, 90 MHz) δ: 14.5 (CH_2CH_3), 17.4 ($CHCH_3$), 18.9 ($CH_2CH_2CH_2$), 19.7 ($CHCH_3$), 21.6 (enol), 29.6 ($CHCH_3$), 29.7 (*enol*, $CHCH_3$), 33.3 ($CH_2CH_2CH_2$), 33.6 (*enol*, $CH_2CH_2CH_2$), 34.4 (enol), 42.3 ($CH_2CH_2CH_2$), 49.5 ($COCH_2CO$), 60.6 (CH_2CH_3), 82.5 (*enol*, CO–CH_2), 84.4 (COCH), 89.8 (*enol*, C=CH), 167.4 (COOCH), 173.2 (COOEt), 177.6 (enol), 202.4 (C=O). IR (ATR, ν cm^{-1}): 2965 (C–H st), 2937 (C–H st), 2876 (C–H st), 1731 (C=O st), 1712 (C=O st), 1464 (CH_3 δ as.), 1311 (C–O–C st as), 1238 (C–O–C st as), 1175 (C–O–C st as), 1131 (C–O–C st as), 1096 (C–O–C st as).

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