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Domino Reactions

Phosphine-Catalyzed Domino Reactions: A Route to Functionalized Bicyclic Skeletons

Erqing Li and You Huang*[a]

Abstract: A novel strategy that involves phosphine-catalyzed sequential [2+3] and [3+2] annulation reactions was developed. In this domino reaction, γ-substituted allenoates were used as novel C_4 synthons, and the bicyclic cyclopenta[*b*]dihydrofuran derivatives were produced in good to excellent diastereoselectivities and yields under mild conditions. Furthermore, preliminary studies on an asymmetric variant of this reaction proceeded with moderate enantioselectivity.

Introduction

Bicyclic and polycyclic skeletons represent privileged structural motifs in natural products, pharmaceuticals, and functional organic materials[1] such as flakinin A, and A,B,D-*seco* limonoid, khayalactone, and Heliconol A, which showed antifungal and antibacterial activities in disk diffusion assays, Bethogenin, and Denfigenin (Figure 1). Enormous efforts have been directed towards the development of efficient and atom-economic ways to construct bi- or polycyclic derivatives. In this field, transition-metal-catalyzed reactions[2] and cooperative transition-metal/organocatalyst catalyzed reactions[3] have become the predominant strategies. The organocatalysts, which are metal-free, usually nontoxic, readily available, and often very robust, have the capability of promoting several types of reactions through different activation modes, however, organocatalyzed reactions that enable the construction of bicyclic compounds remain rare.[4] Thus, the development of an organocatalyzed strategy with which to construct bicyclic compounds should be an attractive and promising challenge for organic and medicinal chemists.

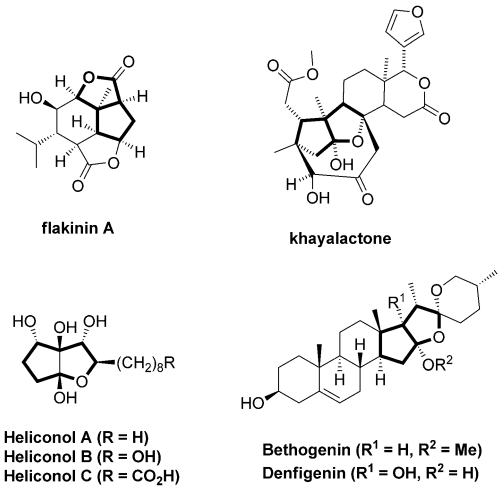

Figure 1. Examples of natural compounds with biological activity incorporating the bicyclic fragment.

Nucleophilic phosphine catalysis has been established as a reliable platform for the efficient assembly of a wide array of cyclic products from simple building blocks.[5] In 1995, Lu et al. were the first to develop a phosphine-catalyzed [3+2] domino annulation reaction to construct monocyclopentene derivatives.[6] Subsequently, Ishar et al. reported the use of a phosphine-catalyzed [4+3] annulation to construct bicyclic compounds.[7]

In further investigations, Lu et al. developed a beautiful [3+2] annulation to construct spirocyclic skeletons with high regioselectivity.[8] Whereas only one ring was obtained in most phosphine-catalyzed domino reactions, under the catalysis of organophosphine a step-economic strategy with which to generate bicyclic compounds by using acyclic substrates seems feasible (Scheme 1).

Recently, we observed that γ-substituted allenoates, which possess lower reactivity due to the presence of a γ-substituent group, are effective substrates in some phosphine-catalyzed domino reactions. Typically, γ-substituted allenoates can function as two-, three-, or four-carbon synthons when reacting with a variety of electrophilic coupling partners (including imines, aldehydes, or alkenes),[7c] undergoing [2+4],[9] [3+2],[10] and [4+2] cycloaddition,[11] and benzannulation reactions.[12] In contrast, phosphine-catalyzed intermolecular cycloaddition reactions to generate bicyclic adducts step-economically have not been exploited. Thus, the development of sequential [2+3] and [3+2] annulation reactions of γ-substitut-

[a] *E. Li, Prof. Dr. Y. Huang*
State Key Laboratory and Institute of Elemento-Organic Chemistry
Collaborative Innovation Center of
Chemical Science and Engineering (Tianjin)
Nankai University, Tianjin 300071 (P. R. China)
Fax: (+86) 22-23503627
E-mail: hyou@nankai.edu.cn

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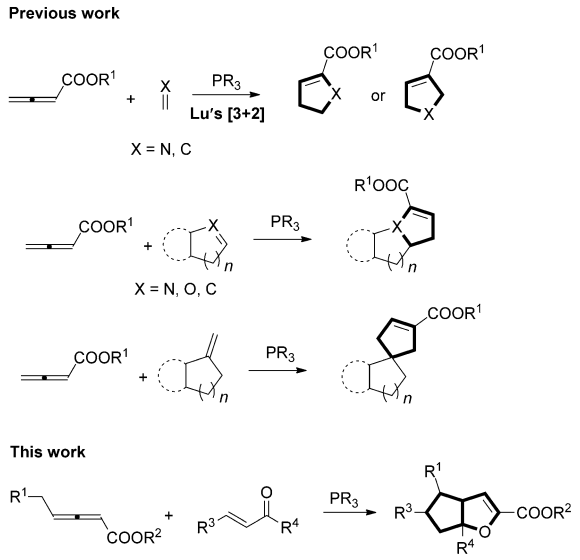
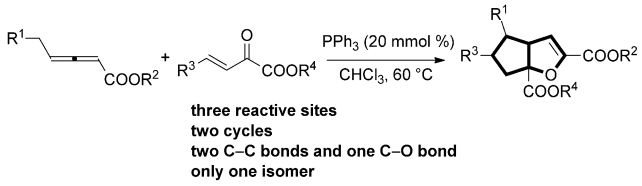


Scheme 1. Pathways for phosphine-catalyzed annulations.



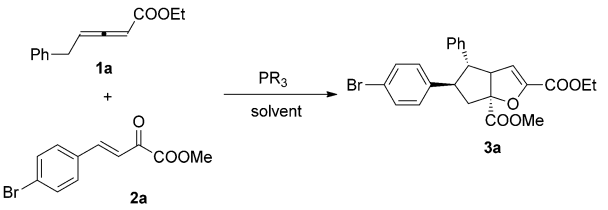
Scheme 2. Highly diastereoselective phosphine-catalyzed, sequential [2+3] and [3+2] annulation reaction of γ-substituted allenoates for the production of cyclopenta[*b*]dihydrofuran derivatives.

ed allenoates to obtain bicyclic adducts is in great demand. Herein, we report a novel phosphine-catalyzed sequential [2+3] and [3+2] annulation reaction for the construction of cyclopenta[*b*]dihydrofuran derivatives. These highly diastereoselective reactions can proceed smoothly in good to excellent yields under mild conditions (Scheme 2).

Results and Discussion

To determine the optimal conditions for phosphine-catalyzed domino annulations,[13] we initiated our screening by using γ-benzyl allenoate **1a** and β,γ-unsaturated α-ketoester **2a** as model substrates. Encouragingly, in the presence of PPh_3 (50 mol%), **1a** and **2a** successfully reacted to form the corresponding cyclopenta[*b*]dihydrofuran derivatives **3a** as a single isomer in 73% yield (Table 1, entry 1). We found that the amount of solvent had a clear influence on the reaction (Table 1, entry 2). When the amount of catalyst was reduced to 20 mol%, 87% yield of **3a** was obtained (Table 1, entry 3). However, when the catalyst loading was reduced further, the reaction proceeded with a slight decrease in yield and longer reaction times were required to obtain full conversion into the product (Table 1, entries 4 and 5). We also found that reducing the temperature did not improve the reaction (Table 1, entries 6 and 7). To further improve this sequential reaction, subsequent investigations into the effect of solvent (CH_3CN, CCl_4, $ClCH_2CH_2Cl$, toluene, and CH_2Cl_2) were conducted, however, the results were not improved (Table 1, entries 8–12). Furthermore, the application of different catalysts demonstrated that triphenylphosphine was the best choice with respect to its catalytic performance, air stability, and low cost. Other catalysts examined, such as $(4\text{-}ClC_6H_4)_3P$, $(4\text{-}MeOC_6H_4)_3P$, and Et_2PPh, gave unsatisfactory results (Table 1, entries 3 and 13–15). On the basis of these experimental results, the best reaction conditions were established as PPh_3 (20 mol%) as the catalyst and $CHCl_3$ as solvent at 60 °C. The structure and stereochemistry of **3** were determined on the basis of a combination of NMR and HRMS analyses and on the single-crystal X-ray analysis of **3o** (Figure 2; see the Supporting Information).[14]

Table 1. Phosphine-catalyzed sequential [2+3] and [3+2] cycloadditions of allenoate **1a** with β,γ-unsaturated α-ketoester **2a**.[a]



Entry	PR_3 ([%])	Solvent	Time [min]	Yield [%][b]
1	PPh_3 (50)	$CHCl_3$	30	73
2[c]	PPh_3 (50)	$CHCl_3$	30	87
3	PPh_3 (20)	$CHCl_3$	30	87
4	PPh_3 (10)	$CHCl_3$	60	86
5	PPh_3 (5)	$CHCl_3$	9 h	73
6[d]	PPh_3 (20)	$CHCl_3$	80	77
7[e]	PPh_3 (20)	$CHCl_3$	10 h	72
8	PPh_3 (20)	CH_3CN	6 h	33
9	PPh_3 (20)	CCl_4	60	71
10	PPh_3 (20)	$ClCH_2CH_2Cl$	45	73
11	PPh_3 (20)	toluene	70	90
12	PPh_3 (20)	CH_2Cl_2	50	80
13	$(4\text{-}ClC_6H_4)_3P$ (20)	$CHCl_3$	90	69
14	$(4\text{-}MeOC_6H_4)_3P$ (20)	$CHCl_3$	40	73
15	$EtPh_2P$ (20)	$CHCl_3$	20	68

[a] Reaction conditions (unless otherwise noted): **1a** (0.4 mmol), **2a** (0.6 mmol), solvent (3 mL), 60 °C. The ratio of **1a**/**2a** was 1:1.5. [b] Yield of isolated product; no other isomers were detected by ^1H NMR spectroscopic analysis. [c] $CHCl_3$ (20 mL) was used. [d] Reaction performed at 40 °C. [e] Reaction performed at 25 °C.

Under the optimized conditions, a series of γ-benzyl allenoates **1** and β,γ-unsaturated α-ketoesters **2** were evaluated for this domino annulation reaction. As shown in Table 2, the reaction shows good tolerance towards the electronic properties of the aromatic substitutes, and high to excellent yields were achieved in all cases (Table 2, entries 1–23). Even with 4-nitro or 2,4-dichloro groups on the benzene rings, high yields and selectivities were still obtained (Table 2, entries 6 and 12). 4-Methoxy groups on the benzene ring led to a slightly lower yield, and required longer reaction times (Table 2, entry 5). The benzene bearing 2,4-chloro groups gave a slightly lower diastereoselectivity (Table 2, entry 12). Furthermore, the steric properties of the γ-benzyl allenoates **1** and the β,γ-unsaturated

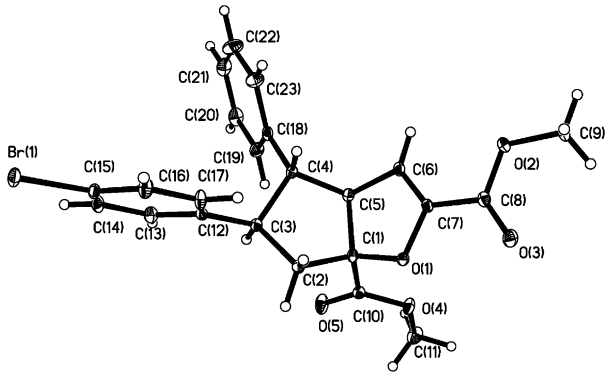
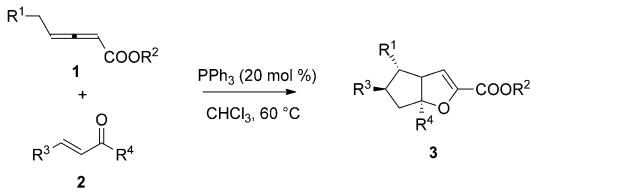


Figure 2. X-ray crystal structure of **3o**.

Table 2. Substrate scope for the synthesis of bicyclic dihydrofuran derivatives.[a]

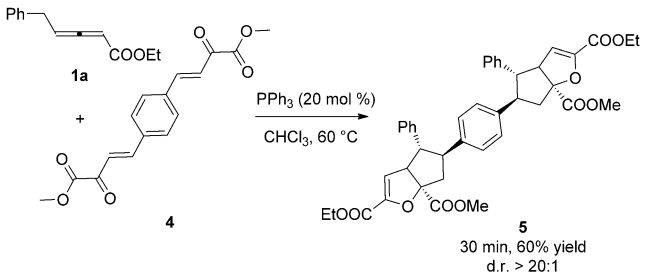


Entry	R^1	R^2	R^3	R^4	Time [min]	3	Yield [%][b]
1	Ph	Et	4-BrC_6H_4	CO_2Me	20	**3a**	87
2	Ph	Et	4-MeC_6H_4	CO_2Me	60	**3b**	98
3	Ph	Et	4-ClC_6H_4	CO_2Me	20	**3c**	93
4	Ph	Et	4-FC_6H_4	CO_2Me	20	**3d**	64
5	Ph	Et	4-$OMeC_6H_4$	CO_2Me	12 h	**3e**	48
6	Ph	Et	4-$NO_2C_6H_4$	CO_2Me	20	**3f**	70
7	Ph	Et	3-BrC_6H_4	CO_2Me	20	**3g**	87
8	Ph	Et	3-MeC_6H_4	CO_2Me	120	**3h**	59
9	Ph	Et	C_6H_5	CO_2Me	20	**3i**	79
10	Ph	Et	2-BrC_6H_4	CO_2Me	10	**3j**	93
11	Ph	Et	2-MeC_6H_4	CO_2Me	120	**3k**	87
12[c]	Ph	Et	2,4-$Cl_2C_6H_3$	CO_2Me	40	**3l**	69
13	Ph	Et	4-BrC_6H_4	CO_2Et	120	**3m**	72
14	Ph	Et	4-BrC_6H_4	CO_2iPr	35	**3n**	83
15	Ph	Me	4-BrC_6H_4	CO_2Me	30	**3o**	84
16	Ph	But	4-BrC_6H_4	CO_2Me	30	**3p**	78
17	Ph	Bn	4-BrC_6H_4	CO_2Me	40	**3q**	74
18	Ph	Et	2-furyl	CO_2Me	120	**3r**	91
19	Ph	Et	2-thienyl	CO_2Me	13 h	**3s**	75
20	Ph	Et	1-naphthyl	CO_2Me	6 h	**3t**	87
21	Ph	Et	styryl	CO_2Me	60	**3u**	92
22[d]	Me	Me	4-BrC_6H_4	CO_2Me	30	**3v**	39
23[e]	Ph	Et	Me	$PO(OEt)_2$	10	**3w**	29

[a] Reaction conditions (unless otherwise noted): **1a** (0.3 mmol), **2a** (0.45 mmol), $CHCl_3$ (3 mL), 60 °C. The ratio of **1a**/**2a** was 1:1.5. [b] Yield of isolated product. [c] d.r. = 93:7. [d] PPh_3 (50 mol%) was used. d.r. = 62:48. [e] PPh_3 (50 mol%) was used. d.r. = 1:1.

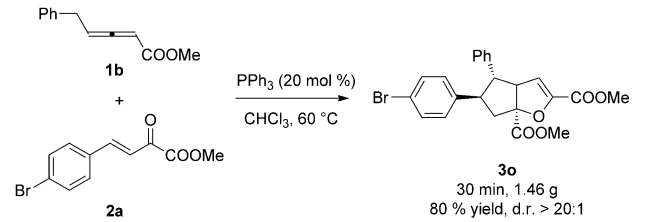
α-ketoesters **2** had a slight effect on the reaction (Table 2, entries 1 and 13–17). The β,γ-unsaturated α-ketoesters bearing 2-furyl, 2-thienyl, and 2-naphthyl groups underwent smooth successive annulations with **1a**, readily affording the corresponding cyclopenta[*b*]dihydrofuran derivatives in excellent yields (Table 2, entries 18–20). We were delighted to find that when methyl 2-oxo-6-phenylhexa-3,5-dienoate was used in the sequential [2+3] and [3+2] annulations with allenoate **1a**, the corresponding product **3u** was obtained in 92% yield (Table 2, entry 21). The reactions of γ-alkyl allenoates as well as diethyl but-2-enoylphosphonate also proceeded smoothly to give the desired products, albeit with moderate yields and lower diastereoselectivity (Table 2, entries 22 and 23). This result indicated that the steric bulk of the substituent group of R^1 and R^3 played a key role in determining the yield and diastereoselectivity.

The phosphine-catalyzed sequential annulation strategy could provide a powerful platform for generating more complex bicyclic compounds. Under the optimized conditions, dimethyl 4,4′-(1,4-phenylene)bis(2-oxobut-3-enoate) (**4**) was used in sequential [2+3] and [3+2] annulations with allenoate **1a** to deliver the desired adduct **5** in good yield. Remarkably, this one-pot reaction generated four rings and six new bonds and gave the product as a single isomer in 60% yield (Scheme 3).



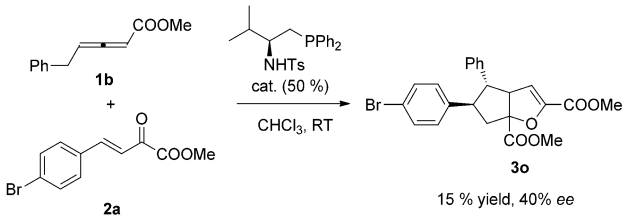
Scheme 3. Phosphine-catalyzed sequential [2+3] and [3+2] cycloaddition of dimethyl 4,4′-(1,4-phenylene)bis(2-oxobut-3-enoate) (**4**) and allenoate **1a**.

To demonstrate the practicality of our method, we performed the sequential [2+3] and [3+2] annulation reaction on a gram scale. When methyl γ-benzyl allenoate **1b** and β,γ-unsaturated α-ketoester **2a** were used under the optimal reaction conditions, the reaction proceed smoothly to afford the desired adduct in 80% yield in 30 minutes (Scheme 4).



Scheme 4. Large-scale phosphine-catalyzed sequential [2+3] and [3+2] annulation between **1b** and **2a**.

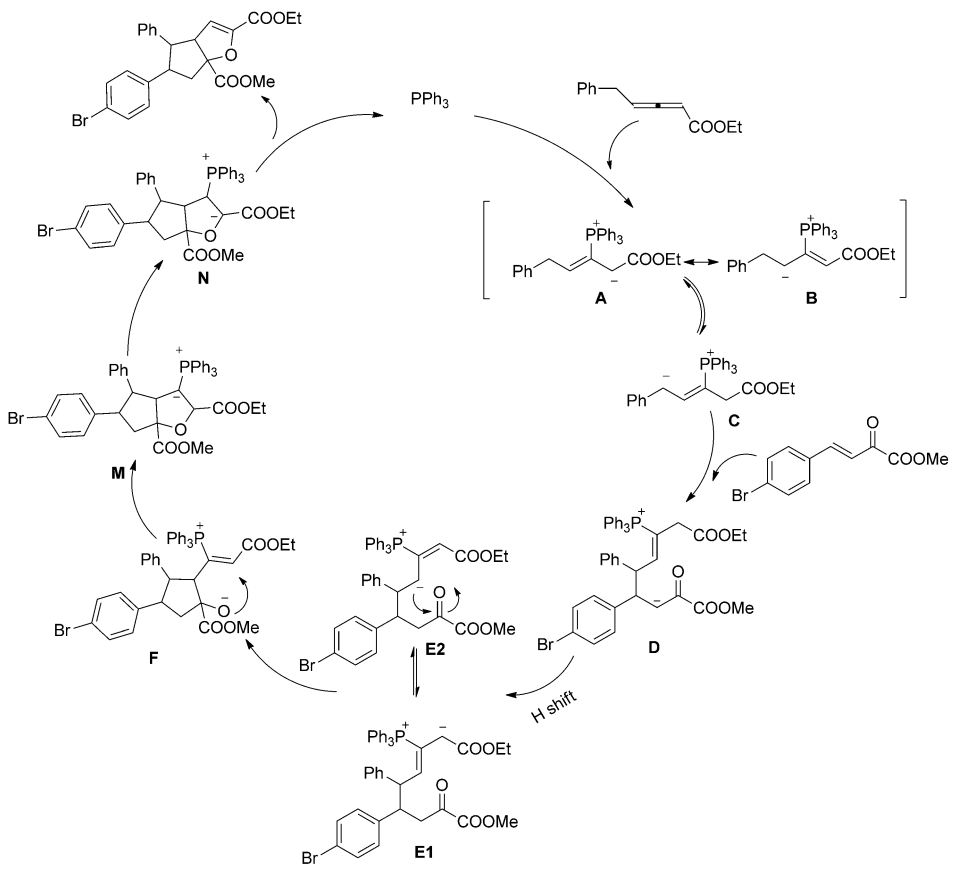
A large number of phosphine-catalyzed annulations have been rendered enantioselective through the use of enantioenriched chiral phosphines.[15] To gauge the feasibility of developing enantioselective annulations, we applied a chiral phosphine in the reaction. To our delight, moderate enantioselectiv-



Scheme 5. Chiral phosphine-catalyzed sequential [2+3] and [3+2] cycloaddition of β,γ-unsaturated α-ketoester **2a** with allenoate **1b**.

ity (40%) was obtained, albeit with a lower yield (15%). Thus, the feasibility of developing an enantioselective process of synthetic value was demonstrated (Scheme 5).

According to our experimental results and related studies,[13a,16] we propose a possible mechanism for this domino reaction (Scheme 6). The crucial event is the formation of the zwitterionic intermediate **C**, which undergoes a sterically favored δ-carbanion addition to the β,γ-unsaturated α-ketoester yielding intermediate **D**. A H-shift then occurs to give intermediates **E1** and **E2** in a reverse equilibrium. Subsequently, nucleophilic addition reaction produces intermediate **F**, which undergoes a second nucleophilic addition to give intermediate **M**. Proton transfer and subsequent β-elimination of the phosphine leads to the formation of the corresponding adducts.



Scheme 6. Mechanism for the phosphine-catalyzed sequential [2+3] and [3+2] cycloaddition of γ-benzyl allenoate **1** and β,γ-unsaturated α-ketoester **2**.

Conclusion

We have developed a novel strategy that involves phosphine-catalyzed sequential [2+3] and [3+2] annulation reactions for the synthesis of cyclopenta[*b*]dihydrofuran derivatives. These cycloaddition reactions are operationally simple and proceed smoothly under mild reaction conditions. An extensive range of substrates was found to afford structurally different oxa-bicyclic derivatives. Chiral phosphine catalysis was also employed in this reaction and moderate enantioselectivity was obtained. The reaction can be performed on a gram scale. Further studies based on the reactivity of γ-substituted allenoates in nucleophilic phosphine catalysis and the development of asymmetric variants of these annulation reactions are ongoing in our laboratories.

Experimental Section

General procedure

To a dry flask filled with nitrogen were added **1** (0.6 mmol), **2** (0.4 mmol) and $CHCl_3$ (3 mL), then PPh_3 (0.08 mmol) was added. The solution was stirred at 60 °C until the reaction was complete (consumption of starting material monitored by TLC). After removal of the solvent, the residue was subjected to chromatography on a silica gel (60–120 mesh; petroleum ether/ethyl acetate 12:1) to afford compound **3**.

2-Ethyl 6a-methyl 5-(4-bromophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3a): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.31 (d, J = 8.4 Hz, 2H), 7.26 (d, J = 7.5 Hz, 2H), 7.21 (d, J = 7.1 Hz, 1H), 7.18–7.15 (m, 2H), 6.97 (t, J = 10.8 Hz, 2H), 6.05 (d, J = 3.0 Hz, 1H), 4.37–4.31 (m, 2H), 3.88 (s, 3H), 3.74 (dd, J = 9.3, 2.9 Hz, 1H), 3.50 (td, J = 12.5, 6.1 Hz, 1H), 3.06 (d, J = 11.5 Hz, 1H), 3.02 (dd, J = 8.6, 4.9 Hz, 1H), 2.49–2.36 (m, 1H), 1.41–1.30 ppm (m, 4H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.4, 159.9, 147.0, 139.7, 138.8, 131.5, 129.1, 128.8, 127.6, 127.2, 120.6, 112.7, 93.5, 77.5, 77.2, 76.9, 61.9, 61.6, 53.0, 51.5, 46.6, 14.3 ppm; IR (KBr): $\tilde{\nu}$ = 2980, 2956, 1733, 1631, 740, 700 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{24}H_{27}O_5BrN^+$: 488.1067 $[M+NH_4]^+$; found: 488.1059.

2-Ethyl 6a-methyl 5-(4-methylphenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3b): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.26–7.21 (m, 2H), 7.17 (dd, J = 6.9, 4.0 Hz, 3H), 6.99 (s, 4H), 6.03 (d, J = 3.0 Hz, 1H), 4.34 (dq, J = 14.3, 7.2 Hz, 2H), 3.85 (s, 2H), 3.74–3.66

(m, 1H), 3.48 (td, J=12.5, 6.2 Hz, 1H), 3.06 (dt, J=18.5, 9.2 Hz, 1H), 2.98 (dd, J=13.6, 6.2 Hz, 1H), 2.49–2.32 (m, 1H), 2.23 (s, 3H), 1.35 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.6, 160.1, 146.9, 140.3, 136.7, 136.3, 129.1, 128.6, 127.6, 127.2, 127.0, 112.9, 93.7, 77.4, 77.1, 76.8, 61.9, 61.5, 61.4, 52.9, 51.5, 47.0, 21.0, 14.3 ppm; IR (KBr): $\tilde{\nu}$=3058, 3028, 2981, 2954, 1733, 1631, 1253, 1231, 740, 701 cm^{-}; HRMS (ESI): m/z calcd for $C_{25}H_{30}O_5N^+$: 424.2118 $[M+NH_4]^+$; found: 424.2125.

2-Ethyl 6a-methyl 5-(4-chlorophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3c): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.23 (d, J=7.5 Hz, 2H), 7.18 (t, J=4.8 Hz, 1H), 7.16–7.12 (m, 4H), 7.01 (d, J=8.4 Hz, 2H), 6.02 (d, J=3.0 Hz, 1H), 4.31 (q, J=7.1 Hz, 2H), 3.85 (s, 3H), 3.72 (dd, J=9.3, 2.9 Hz, 1H), 3.48 (td, J=12.5, 6.2 Hz, 1H), 3.03 (d, J=11.4 Hz, 1H), 2.99 (dd, J=8.5, 5.0 Hz, 1H), 2.39 (t, J=13.3 Hz, 1H), 1.34 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.4, 159.9, 147.0, 139.7, 138.3, 132.5, 128.8, 128.7, 128.6, 127.5, 127.2, 112.7, 93.5, 77.5, 77.2, 76.8, 61.8, 61.6, 61.5, 53.0, 51.4, 46.6, 14.2 ppm; IR (KBr): $\tilde{\nu}$=3062, 3030, 2982, 2954, 1733, 1632, 1254, 1232, 742, 701 cm^{-}; HRMS (ESI): m/z calcd for $C_{24}H_{27}O_5NCl^+$: 444.1572 $[M+NH_4]^+$; found: 444.1579.

2-Ethyl 6a-methyl 5-(4-fluorophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3d): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.24 (d, J=7.5 Hz, 2H), 7.19 (d, J=7.2 Hz, 1H), 7.14 (d, J=7.1 Hz, 2H), 7.04 (dd, J=8.5, 5.4 Hz, 2H), 6.86 (t, J=8.7 Hz, 2H), 6.02 (d, J=3.0 Hz, 1H), 4.32 (q, J=7.1 Hz, 2H), 3.86 (s, 3H), 3.72 (dd, J=9.3, 2.9 Hz, 1H), 3.49 (td, J=12.5, 6.2 Hz, 1H), 3.05–3.01 (m, 1H), 2.99 (t, J=7.5 Hz, 1H), 2.39 (t, J=13.3 Hz, 1H), 1.35 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.5, 162.9, 160.5, 160.0, 147.0, 139.9, 135.4, 135.4, 128.8, 128.7, 128.7, 127.6, 127.2, 115.4, 115.1, 112.8, 93.5, 77.4, 77.1, 76.8, 61.8, 61.5, 53.0 51.3, 46.7, 14.2 ppm; IR (KBr): $\tilde{\nu}$=3062, 3030, 2982, 2956, 1733, 1632, 1230, 740, 700 cm^{-}; HRMS (ESI): m/z calcd for $C_{24}H_{27}O_5NF^+$: 428.1868 $[M+NH_4]^+$; found: 428.1871.

2-Ethyl 6a-methyl 5-(4-methoxyphenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3e): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.23 (d, J=7.5 Hz, 2H), 7.21–7.13 (m, 3H), 7.00 (d, J=8.6 Hz, 2H), 6.72 (d, J=8.6 Hz, 2H), 6.03 (d, J=3.0 Hz, 1H), 4.32 (q, J=7.1 Hz, 2H), 3.86 (s, 3H), 3.71 (s, 3H), 3.69 (d, J=3.0 Hz, 1H), 3.46 (td, J=12.5, 6.2 Hz, 1H), 3.03 (dd, J=11.3, 9.1 Hz, 1H), 2.97 (dd, J=13.5, 6.1 Hz, 1H), 2.39 (t, J=13.3 Hz, 1H), 1.35 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.6, 160.1, 158.4, 146.9, 140.3, 131.7, 128.6, 128.2, 127.6, 127.0, 113.8, 112.9, 93.59, 61.8, 61.6, 61.5, 55.1, 52.9, 51.2, 46.9, 14.2 ppm; IR (KBr): $\tilde{\nu}$=3062, 3030, 2981, 2955, 1733, 1632, 1248, 740, 701 cm^{-}; HRMS (ESI): m/z calcd for $C_{25}H_{30}O_6N^+$: 440.2068 $[M+NH_4]^+$; found: 440.2072.

2-Ethyl 6a-methyl 5-(4-nitrophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3f): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.94 (d, J=8.7 Hz, 2H), 7.17 (dd, J=12.1, 5.6 Hz, 4H), 7.12 (d, J=7.0 Hz, 1H), 7.06 (d, J=7.0 Hz, 2H), 5.95 (d, J=2.9 Hz, 1H), 4.24 (q, J=7.1 Hz, 2H), 3.79 (s, 3H), 3.67 (dd, J=9.2, 2.9 Hz, 1H), 3.54 (td, J=12.5, 6.1 Hz, 1H), 3.00 (t, J=7.2 Hz, 1H), 2.97 (dd, J=7.5, 6.0 Hz, 1H), 2.37 (t, J=13.2 Hz, 1H), 1.27 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.2, 159.8, 147.6, 147.2, 146.9, 139.1, 128.9, 128.2, 127.5, 127.4, 123.7, 112.4, 93.4, 77.5, 77.1, 76.8, 61.9, 61.8, 61.6, 53.1, 51.8, 46.3, 14.2 ppm; IR (KBr): $\tilde{\nu}$=3063, 3029, 2982, 2955, 1732, 1631, 1232, 742, 700 cm^{-}; HRMS (ESI): m/z calcd for $C_{24}H_{27}O_7N_2^+$: 455.1813 $[M+NH_4]^+$; found: 455.1819.

2-Ethyl 6a-methyl 5-(3-bromophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3g): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.30–7.26 (m, 4H), 7.22 (d, J=7.1 Hz, 1H), 7.20–7.16 (m, 2H), 7.09–6.97 (m, 2H), 6.05 (d, J=3.0 Hz, 1H), 4.34 (q, J=7.1 Hz, 2H), 3.88 (s, 3H), 3.74 (dd, J=9.2, 3.0 Hz, 1H), 3.50 (td, J=12.5, 6.2 Hz, 1H), 3.09 (dd, J=12.2, 9.8 Hz, 1H), 3.03 (dd, J=13.8, 6.4 Hz, 1H), 2.41 (t, J=13.3 Hz, 1H), 1.37 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.4, 159.9, 147.1, 142.3, 139.6, 130.3, 130.0, 128.8, 127.5, 127.3, 126.2, 122.6, 112.7, 93.5, 77.5, 77.2, 76.8, 61.9, 61.6, 61.4, 53.0, 51.6, 46.7, 14.3 ppm; IR (KBr): $\tilde{\nu}$=3060 3029, 2981, 2954, 1734, 1632, 1232, 740, 702 cm^{-}; HRMS (ESI): m/z calcd for $C_{24}H_{27}O_5BrN^+$; 488.1067 $[M+NH_4]^+$; found: 488.1073.

2-Ethyl 6a-methyl 5-(3-methylphenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3h): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.26–7.20 (m, 2H), 7.17 (d, J=7.2 Hz, 3H), 7.05 (t, J=7.8 Hz, 1H), 6.95–6.86 (m, 3H), 6.04 (d, J=3.0 Hz, 1H), 4.31 (q, J=7.1 Hz, 2H), 3.84 (s, 3H), 3.71 (dd, J=9.3, 2.9 Hz, 1H), 3.48 (td, J=12.5, 6.2 Hz, 1H), 3.10 (dd, J=11.6, 9.4 Hz, 1H), 2.99 (dd, J=13.6, 6.2 Hz, 1H), 2.41 (t, J=13.3 Hz, 1H), 2.22 (s, 3H), 1.34 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.5, 160.1, 147.0, 140.3, 139.7, 137.9, 128.7, 128.3, 128.0, 127.6, 127.0, 124.5, 112.9, 93.7, 77.5, 77.2, 76.8, 61.9, 61.5, 61.3, 52.9, 51.8, 47.1, 21.4, 14.3 ppm; IR (KBr): $\tilde{\nu}$=3062, 3030, 2982, 2955, 1733, 1631, 1232, 742, 700 cm^{-}; HRMS (ESI): m/z calcd for $C_{25}H_{30}O_5N^+$: 424.2118 $[M+NH_4]^+$; found: 424.2125.

2-Ethyl 6a-methyl 4,5-diphenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3i): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.26–7.21 (m, 2H), 7.16 (tdd, J=10.6, 7.4, 3.2 Hz, 6H), 7.10 (dd, J=7.4, 5.9 Hz, 3H), 6.03 (d, J=3.0 Hz, 1H), 4.32 (q, J=7.1 Hz, 2H), 3.85 (s, 3H), 3.72 (dd, J=9.3, 2.9 Hz, 1H), 3.51 (td, J=12.6, 6.2 Hz, 1H), 3.09 (dd, J=11.7, 9.3 Hz, 1H), 3.01 (dd, J=13.6, 6.2 Hz, 1H), 2.51–2.36 (m, 1H), 2.43 (t, J=13.3 Hz, 1H), 1.34 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.5, 160.1, 147.0, 140.2, 139.8, 128.7, 128.4, 127.6, 127.4, 127.1, 126.9, 112.9, 93.7, 77.5, 77.2, 76.8, 61.9, 61.6, 61.5, 53.0, 51.0, 46.9, 14.3 ppm; IR (KBr): $\tilde{\nu}$=3062, 3028, 2957, 1733, 1632, 1257, 1233, 743, 701 cm^{-}; HRMS (ESI): m/z calcd for $C_{24}H_{28}O_5N^+$: 410.1962 $[M+NH_4]^+$; found: 410.1968.

2-Ethyl 6a-methyl 5-(2-bromophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3j): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.43 (dd, J=8.0, 1.0 Hz, 1H), 7.32 (dd, J=7.9, 1.4 Hz, 1H), 7.25–7.14 (m, 6H), 6.98 (td, J=7.8, 1.6 Hz, 1H), 6.08 (t, J=4.9 Hz, 1H), 4.33 (q, J=7.1 Hz, 2H), 4.18 (td, J=12.4, 6.2 Hz, 1H), 3.87 (s, 3H), 3.67 (dd, J=9.3, 3.0 Hz, 1H), 3.30 (dd, J=12.0, 9.4 Hz, 1H), 3.14 (dd, J=13.4, 6.2 Hz, 1H), 2.18 (dt, J=26.2, 12.5 Hz, 1H), 1.35 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.2, 160.0, 147.3, 139.3, 139.0, 133.1, 128.7, 128.3, 127.7, 127.6, 127.2, 125.5, 112.8, 93.4, 77.4, 77.1, 76.8, 61.7, 61.6, 59.7, 53.0, 49.4, 46.4, 14.3 ppm; IR (KBr): $\tilde{\nu}$=3064, 3030, 2982, 2955, 1734, 1632, 1253, 1232, 744, 701 cm^{-}; HRMS (ESI): m/z calcd for $C_{24}H_{27}O_5BrN^+$: 488.1067 $[M+NH_4]^+$; found: 488.1064.

2-Ethyl 6a-methyl 4-phenyl-5-(*o*-tolyl)-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[b]furan-2,6a-dicarboxylate (3k): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.31 (d, J=7.7 Hz, 1H), 7.21–7.18 (m, 2H), 7.17–7.11 (m, 4H), 7.01 (d, J=6.8 Hz, 2H), 6.06 (d, J=3.0 Hz, 1H), 4.32 (q, J=7.1 Hz, 2H), 3.86 (s, 3H), 3.81 (dd, J=12.3, 6.3 Hz, 1H), 3.74 (dd, J=9.2, 2.9 Hz, 1H), 3.23 (dd, J=11.7, 9.3 Hz, 1H), 2.99 (dd, J=13.5, 6.1 Hz, 1H), 2.25 (t, J=13.2 Hz, 1H), 2.12 (s, 3H), 1.35 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.7, 160.1, 147.1, 140.0, 138.0, 136.7, 130.3, 128.6, 127.5, 127.0, 126.4, 126.3, 125.3, 112.9, 93.6, 77.5, 77.1, 76.8, 61.5, 61.5, 60.6, 52.9, 47.25, 46.9, 19.5, 14.3 ppm; IR (KBr): $\tilde{\nu}$=3061, 3029, 2981, 2954, 1733, 1631, 1255, 1231, 743, 700 cm^{-}; HRMS (ESI): m/z calcd for $C_{25}H_{30}O_5N^+$: 424.2118 $[M+NH_4]^+$; found: 424.2118.

2-Ethyl 6a-methyl 5-(2,4-dichlorophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3l): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.30–7.09 (m, 8H), 6.07 (d, J = 2.8 Hz, 1H), 4.32 (q, J = 14.2, 7.1 Hz, 2H), 4.12 (td, J = 12.3, 6.2 Hz, 1H), 3.87 (s, 3H), 3.67 (dd, J = 9.2, 2.6 Hz, 1H), 3.24 (dd, J = 11.8, 9.6 Hz, 1H), 3.10 (dd, J = 13.4, 6.2 Hz, 1H), 2.16 (t, J = 13.1 Hz, 1H), 1.35 ppm (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.1, 159.9, 147.3, 139.0, 136.0, 135.3, 132.9, 129.5, 128.8, 128.1, 127.5, 127.4, 127.4, 112.6, 93.4, 77.5, 77.1, 76.8, 61.6, 61.6, 59.8, 53.0, 46.5, 46.0, 14.2 ppm; IR (KBr): $\tilde{\nu}$ = 3062, 3029, 2982, 2954, 1733, 1632, 1254, 1232, 742, 699 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{24}H_{26}O_5Cl_2N^+$: 478.1183 $[M+NH_4]^+$; found: 478.1182.

Diethyl 5-(4-bromophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3m): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.28 (d, J = 8.4 Hz, 2H), 7.23 (d, J = 7.5 Hz, 2H), 7.20–7.17 (m, 1H), 7.16–7.12 (m, 2H), 6.95 (d, J = 8.4 Hz, 2H), 6.02 (d, J = 3.0 Hz, 1H), 4.36–4.27 (m, 4H), 3.71 (dd, J = 9.3, 3.0 Hz, 1H), 3.55–3.38 (m, 1H), 3.02 (dd, J = 9.6, 6.8 Hz, 1H), 2.99 (dd, J = 9.3, 4.1 Hz, 1H), 2.51–2.31 (m, 1H), 1.38–1.31 ppm (m, 6H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 172.8, 160.0, 147.1, 139.8, 138.9, 131.5, 129.1, 128.8, 127.5, 127.2, 120.6, 112.7, 93.5, 77.5, 77.2, 76.9, 62.0, 61.8, 61.6, 61.5, 51.5, 46.5, 14.2, 14.2 ppm; IR (KBr): $\tilde{\nu}$ = 3062, 3029, 2981, 2937, 1731, 1632, 1231, 742, 701 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{25}H_{29}O_5BrN^+$: 502.1224 $[M+NH_4]^+$; found: 502.1221.

2-Ethyl 6a-isopropyl 5-(4-bromophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3n): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.33–7.27 (m, 2H), 7.25 (d, J = 7.5 Hz, 2H), 7.20 (dd, J = 5.4, 1.7 Hz, 1H), 7.15–7.12 (m, 2H), 6.95 (d, J = 8.4 Hz, 2H), 6.01 (d, J = 3.0 Hz, 1H), 5.21–5.11 (m, 1H), 4.35–4.29 (m, 2H), 3.01 (dd, J = 9.8, 7.3 Hz, 1H), 2.97 (dd, J = 11.6, 4.2 Hz, 1H), 2.46–2.29 (m, 1H), 1.41–1.30 ppm (m, 9H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 172.1, 160.0, 147.1, 139.9, 139.0, 131.5, 129.0, 128.8, 127.5, 127.2, 120.6, 112.6, 93.5, 77.4, 77.1, 76.8, 69.8, 61.8, 61.6, 61.5, 51.6, 46.5, 21.7, 14.2 ppm; IR (KBr): $\tilde{\nu}$ = 3064, 3030, 2981, 2936, 1734, 1628, 1230, 741, 701 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{26}H_{31}O_5BrN^+$: 516.1380 $[M+NH_4]^+$; found: 516.1379.

Dimethyl 5-(4-bromophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3o): White solid; m.p. 135–136 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.30 (d, J = 8.4 Hz, 2H), 7.27–7.23 (m, 2H), 7.20 (d, J = 7.1 Hz, 1H), 7.13 (d, J = 7.0 Hz, 2H), 6.95 (d, J = 8.4 Hz, 2H), 6.04 (d, J = 3.0 Hz, 1H), 3.87 (s, 3H), 3.86 (s, 3H), 3.71 (dd, J = 9.3, 3.0 Hz, 1H), 3.47 (td, J = 12.5, 6.2 Hz, 1H), 3.01 (dd, J = 8.6, 5.8 Hz, 1H), 2.99 (dd, J = 11.7, 4.6 Hz, 1H), 2.38 (t, J = 13.3 Hz, 1H), 1.63 ppm (dd, J = 5.0, 2.8 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.4, 160.3, 146.7, 139.6, 138.7, 131.5, 129.0, 128.8, 127.5, 127.3, 120.6, 113.1, 93.6, 77.4, 77.1, 76.7, 61.8, 61.6, 53.0, 52.4, 51.4, 46.6 ppm; IR (KBr): $\tilde{\nu}$ = 3062, 3029, 2952, 1733, 1631, 1257, 1233, 742, 701 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{23}H_{25}O_5BrN^+$: 474.0911 $[M+NH_4]^+$; found: 474.0907.

2-*tert*-Butyl 6a-methyl 5-(4-bromophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3p): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.29 (d, J = 8.4 Hz, 2H), 7.27–7.23 (m, 2H), 7.19 (d, J = 7.2 Hz, 1H), 7.14 (d, J = 7.0 Hz, 2H), 6.95 (d, J = 8.4 Hz, 2H), 5.86 (d, J = 2.9 Hz, 1H), 3.86 (s, 3H), 3.70 (dt, J = 8.4, 4.2 Hz, 1H), 3.43 (td, J = 12.5, 6.1 Hz, 1H), 3.01 (dd, J = 8.9, 6.5 Hz, 1H), 2.99–2.93 (m, 1H), 2.38 (t, J = 13.3 Hz, 1H), 1.54 ppm (s, 9H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.6, 159.1, 147.9, 139.9, 138.9, 131.5, 129.1, 128.7, 127.6, 127.2, 120.6, 111.4, 93.2, 82.5, 77.4, 77.1, 76.7, 61.7, 61.6, 52.9, 51.6, 46.5, 28.1 ppm; IR (KBr): $\tilde{\nu}$ = 3062, 3029, 2979, 2953, 1730, 1632, 1258, 1233, 742, 701 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{26}H_{31}O_5BrN^+$: 516.1380 $[M+NH_4]^+$; found: 516.1378.

2-Benzyl 6a-methyl 5-(4-bromophenyl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3q): White solid; m.p. 132–133 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.40 (t, J = 6.9 Hz, 2H), 7.36 (d, J = 7.6 Hz, 2H), 7.28 (d, J = 8.2 Hz, 2H), 7.22 (d, J = 7.6 Hz, 2H), 7.18 (d, J = 6.9 Hz, 1H), 7.12 (d, J = 7.2 Hz, 2H), 6.94 (d, J = 8.3 Hz, 2H), 6.03 (d, J = 2.9 Hz, 1H), 5.28 (s, 2H), 3.85 (s, 3H), 3.72 (dd, J = 9.3, 2.9 Hz, 1H), 3.45 (td, J = 12.5, 6.2 Hz, 1H), 3.01 (dd, J = 8.4, 6.0 Hz, 1H), 2.98 ppm (dd, J = 12.0, 4.8 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.4, 159.8, 146.8, 139.7, 138.8, 135.3, 131.5, 129.1, 128.8, 128.7, 128.7, 128.6, 127.6, 127.3, 120.6, 113.2, 93.5, 77.4, 77.1, 76.8, 67.1, 61.9, 61.5, 53.0, 51.5, 46.6 ppm. IR (KBr): $\tilde{\nu}$ = 3063, 3030, 2953, 1732, 1630, 1261, 1230, 742, 699 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{29}H_{29}O_5BrN^+$: 550.1224 $[M+NH_4]^+$; found: 550.1214.

2-Ethyl 6a-methyl 5-(furan-2-yl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3r): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.32–7.26 (m, 2H), 7.22 (dd, J = 6.9, 4.0 Hz, 3H), 7.03 (d, J = 4.7 Hz, 1H), 6.78 (dd, J = 5.0, 3.6 Hz, 1H), 6.64 (d, J = 3.4 Hz, 1H), 6.00 (d, J = 3.0 Hz, 1H), 4.31 (q, J = 7.1 Hz, 2H), 3.85 (s, 3H), 3.79 (dd, J = 12.2, 6.1 Hz, 1H), 3.70 (dd, J = 9.3, 3.0 Hz, 1H), 3.12 (dd, J = 13.5, 6.1 Hz, 1H), 3.03 (dd, J = 11.5, 9.4 Hz, 1H), 2.45 (t, J = 13.1 Hz, 1H), 1.33 ppm (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.3, 159.9, 147.0, 143.6, 139.9, 128.8, 127.8, 127.3, 126.6, 124.3, 123.4, 112.6, 93.3, 77.5, 77.2, 76.9, 62.4, 62.2, 61.6, 53.0, 47.4, 47.1, 14.2 ppm; IR (KBr): $\tilde{\nu}$ = 3062, 3030, 2981, 2956, 1733, 1632, 1237, 739, 701 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{22}H_{26}O_6N^+$: 400.1755 $[M+NH_4]+$; found: 400.1755.

2-Ethyl 6a-methyl 4-phenyl-5-(thiophen-2-yl)-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3s): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.33–7.27 (m, 2H), 7.26–7.20 (m, 3H), 7.05 (d, J = 5.1 Hz, 1H), 6.80 (dd, J = 5.0, 3.6 Hz, 1H), 6.64 (d, J = 3.4 Hz, 1H), 6.01 (d, J = 3.0 Hz, 1H), 4.32 (q, J = 7.1 Hz, 2H), 3.86 (s, 3H), 3.83–3.76 (m, 1H), 3.69 (dd, J = 9.3, 2.9 Hz, 1H), 3.12 (dd, J = 13.5, 6.2 Hz, 1H), 3.03 (dd, J = 11.4, 9.5 Hz, 1H), 2.45 (t, J = 13.1 Hz, 1H), 1.35 ppm (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.4, 160.0, 147.0, 143.6, 139.9, 128.8, 127.8, 127.3, 126.5, 124.3, 123.4, 112.6, 93.3, 77.4, 77.0, 76.7, 62.4, 62.2, 61.6, 53.0, 47.4, 47.1, 14.2 ppm; IR (KBr): $\tilde{\nu}$ = 3064, 3029, 2981, 2955, 1733, 1632, 1235, 742, 700 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{22}H_{26}O_5NS^+$: 416.1526 $[M+NH_4]^+$; found: 416.1527.

2-Ethyl 6a-methyl 5-(naphthalen-1-yl)-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3t): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.17 (d, J = 8.5 Hz, 1H), 7.77 (t, J = 7.6 Hz, 1H), 7.76 (d, J = 8.1 Hz, 1H), 7.63 (d, J = 8.1 Hz, 1H), 7.63 (d, J = 8.1 Hz, 1H), 7.50 (t, J = 7.3 Hz, 1H), 7.42 (d, J = 7.4 Hz, 2H), 7.31 (t, J = 7.7 Hz, 1H), 7.25 (d, J = 7.5 Hz, 2H), 7.16 (t, J = 7.5 Hz, 2H), 7.08 (t, J = 7.3 Hz, 1H), 6.16 (t, J = 4.3 Hz, 1H), 4.48 (td, J = 12.4, 5.9 Hz, 1H), 4.31 (q, J = 7.1 Hz, 2H), 3.89 (s, 3H), 3.74 (dd, J = 9.2, 2.9 Hz, 1H), 3.57 (dd, J = 11.6, 9.4 Hz, 1H), 3.27 (dt, J = 14.6, 7.3 Hz, 1H), 2.24 (t, J = 13.2 Hz, 1H), 1.33 ppm (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ = 173.9, 160.1, 147.4, 140.0, 135.9, 133.9, 132.5, 128.9, 128.8, 127.5, 127.3, 127.1, 126.3, 125.6, 125.5, 123.1, 122.8, 112.9, 93.4, 77.5, 77.2, 76.9, 62.3, 61.6, 58.5, 53.1, 47.5, 45.7, 14.3 ppm; IR (KBr): $\tilde{\nu}$ = 3061, 3030, 2980, 2955, 1732, 1632, 1255, 1232, 738, 700 cm^{-}; HRMS (ESI): *m/z* calcd for $C_{28}H_{30}O_5N^+$: 460.2118 $[M+NH_4]^+$; found: 460.2121.

2-Ethyl 6a-methyl 4-phenyl-5-((*E*)-styryl)-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3u): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.22 (d, J = 7.3 Hz, 2H), 7.17 (d, J = 7.4 Hz, 2H), 7.12 (d, J = 6.1 Hz, 4H), 7.06 (td, J = 6.0, 2.5 Hz, 1H), 6.18 (d, J = 15.9 Hz, 1H), 5.91 (d, J = 3.1 Hz, 1H), 5.89 (dd, J = 13.6, 5.1 Hz, 1H), 4.30–4.10 (m, 2H), 3.75 (s, 3H), 3.57 (dd, J = 9.2, 2.9 Hz, 1H), 3.10–2.98 (m, 1H), 2.82 (dd, J = 13.5, 6.1 Hz, 1H), 2.74 (dd, J =

11.1, 9.5 Hz, 1H), 2.12 (t, J=12.9 Hz, 1H), 1.24 ppm (t, J=7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.4, 160.0, 146.9, 140.3, 137.0, 131.4, 129.3, 128.8, 128.5, 127.7, 127.3, 127.2, 126.1, 112.9, 94.0, 77.5, 77.2, 76.9, 62.1, 61.5, 60.5, 52.9, 49.8, 45.2, 14.3 ppm; IR (KBr): $\tilde{\nu}$=3060, 3028, 2981, 2956, 1733, 1636, 1253, 1231, 743, 698 cm^{-}; HRMS (ESI): m/z calcd for $C_{26}H_{30}O_5N^+$: 436.2118 $[M+NH_4]^+$; found: 436.2121.

Dimethyl 5-(4-bromophenyl)-4-methyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate (3v): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.43–7.41 (m, 2H), 7.04 (d, J=8.3 Hz, 2H), 5.93 (d, J=3.1 Hz, 1H), 3.85 (s, 3H), 3.83 (s, 3H), 3.53 (dt, J=13.0, 5.8 Hz, 1H), 3.44 (d, J=3.1 Hz, 1H), 2.82–2.74 (m, 2H), 2.42 (dd, J=13.6, 5.7 Hz, 1H), 2.35–2.27 (m, 1H), 0.73 ppm (d, J=7.3 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.4, 172.8, 160.4, 160.1, 148.3, 146.8, 139.6, 138.4, 131.7, 131.4, 129.6, 129.2, 120.6, 120.2, 113.3, 113.2, 95.2, 94.0, 60.9, 60.8, 53.0, 52.9, 52.4, 52.0, 50.6, 46.6, 45.2, 44.7, 38.5, 16.5, 15.2 ppm; IR (KBr): $\tilde{\nu}$=3061, 3030, 2954, 1732, 1641, 1246, 743, 701 cm^{-}; HRMS (ESI): m/z calcd for $C_{18}H_{19}BrO_5N^+$: 417.0308 $[M+Na]^+$; found: 417.0317.

Ethyl 6a-(diethoxyphosphoryl)-5-methyl-4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2-carboxylate (3w): Colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.32 (d, J=7.4 Hz, 2H), 7.24 (d, J=7.4 Hz, 3H), 5.98 (t, J=9.0 Hz, 1H), 4.34–4.20 (m, 6H), 3.79–3.63 (m, 1H), 2.88 (td, J=14.3, 5.8 Hz, 1H), 2.46 (t, J=10.2 Hz, 1H), 2.27 (dt, J=17.7, 6.0 Hz, 1H), 1.84 (dt, J=18.4, 12.8 Hz, 1H), 1.41–1.28 (m, 9H), 0.90 ppm (d, J=6.3 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=159.1, 145.4, 145.3, 140.2, 127.7, 126.6, 125.9, 113.1, 113.0, 91.5, 89.8, 62.5, 62.4, 62.3, 61.3, 61.2, 60.2, 58.9, 44.4, 44.4, 40.0, 15.8, 15.6, 15.5, 15.5, 13.1 ppm; ^{31}P NMR (162 MHz, $CDCl_3$): δ=20.74 ppm; IR (KBr): $\tilde{\nu}$=3061, 3029, 2981, 2960, 1733, 1633, 1245, 744, 702 cm^{-}; HRMS (ESI): m/z calcd for $C_{21}H_{29}PO_6Na^+$: 431.1594 $[M+Na]^+$; found: 431.1597.

Diethyl 6a-dimethyl 5,5′-(1,4-phenylene)bis(4-phenyl-4,5,6,6a-tetrahydro-3a*H*-cyclopenta[*b*]furan-2,6a-dicarboxylate) (5): White solid; m.p. 96–97 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ=7.23–7.15 (m, 6H), 7.09–7.05 (m, 4H), 6.88 (d, J=4.1 Hz, 4H), 5.99 (t, J=3.0 Hz, 2H), 4.30 (q, J=7.1 Hz, 4H), 3.83 (s, 6H), 3.69 (dt, J=9.2, 3.1 Hz, 2H), 3.39 (tt, J=11.5, 5.8 Hz, 2H), 3.01–2.95 (m, 2H), 2.95–2.90 (m, 2H), 2.35 (td, J=13.3, 5.7 Hz, 2H), 1.33 ppm (t, J=7.1 Hz, 6H); ^{13}C NMR (101 MHz, $CDCl_3$): δ=173.4, 160.0, 146.9, 140.1, 138.3, 128.6, 128.5, 127.6, 127.6, 127.3, 127.0, 127.0, 112.9, 93.6, 93.6, 77.5, 77.2, 76.9, 61.6, 61.6, 61.5, 61.4, 52.9, 51.7, 51.5, 46.5, 46.4, 14.2 ppm; IR (KBr): $\tilde{\nu}$=3061, 3029, 2955, 1732, 1642, 1245, 743, 701 cm^{-}; HRMS (ESI): m/z calcd for $C_{42}H_{46}O_{10}NNa^+$: 729.2670 $[M+Na]^+$; found: 729.2664.

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