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Gold(I) catalysed cycloisomerisation of β-hydroxy propargylic esters to dihydropyrans/2*H*-pyrans via allene intermediates

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ABSTRACT

Efficient cycloisomerisation of β-hydroxy propargylic esters to dihydropyrans/2*H*-pyrans via 1,3-carboxylate migration followed by regioselective hydroxyl addition to the transient allene intermediate catalysed by $Ph_3PAuCl/AgSbF_6$ is presented. Similar reactions on phosphorylated precursors led to phosphono-furans and phosphono-pyrans. In a few cases, self-condensation of β-hydroxy propargylic esters via catalytic nucleophilic substitution to macrocycles is observed. Key products are characterised by X-ray structure determination.

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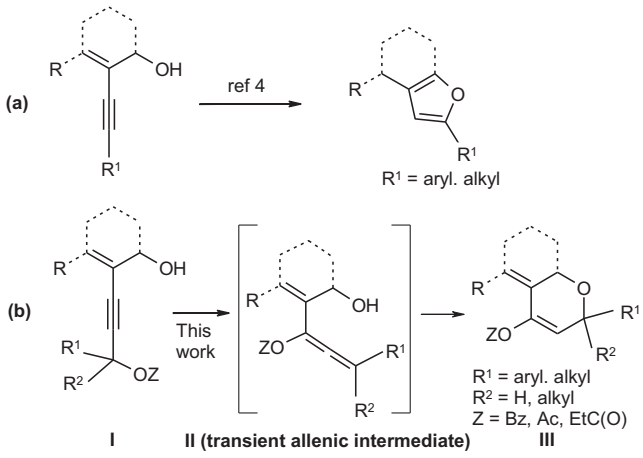
1. Introduction

Thanks to the recent flurry of activity, gold catalysis has now been proven to be an effective method for the construction of C–C and C–X bonds.[1] Mild conditions like low catalyst loading, short reaction time, ambient temperature conversions for regio- and stereo-selective transformations involving highly functionalized molecules have rendered gold catalysis an active area of research.[2] As a consequence of alkynophilicity of gold salts, alkynols as well as propargylic esters can be made to undergo rearrangement to provide a variety of reactivity patterns.[2a,3] Only a handful of reports on the use of 2-alkynyl allyl alcohols to synthesise functionalised carbocycles/furans via gold[4] or silver[5] catalysis are available. Our recent discovery[4e] in using 2-alkynyl cinnamyl alcohols for the synthesis of furans prompted us to examine a feasible six-membered (pyran) ring formation instead of furans. Dihydropyran ring system is fairly common in biologically active natural products like laulimalide,[6a–c] ambruticin S,[6d] Scytophycin C,[6e] swinhol,[6f,g] methyl sarcophytoate,[6h] which have anticancer, antifungal and antibiotic activity.[7] They are also valuable synthetic scaffolds for the generation of natural products,[8] carbohydrates and functionalized pyridines.[9] 2*H*-Pyran is also an important skeleton in biological molecules like pyranoflavanoids.[10] De Brabander and co-workers have recently reported the cycloisomerisation of ω-hydroxy propargylic esters to lead to tetrahydropyrans via 1,3-acyloxy migration.[11] Considering the behaviour of propargylic ester group in the presence of gold complexes, we synthesised β-hydroxy propargylic esters **I** (Scheme 1) with a view to generate six-membered oxacycles (pyrans). The reaction is supposed to proceed through allenic intermediate **II**, which on hydroxyl addition to the allene could lead to pyran derivatives **III**.



Scheme 1. Cycloisomerisation of 2-alkynyl allyl alcohols: (a) reported, (b) proposed.

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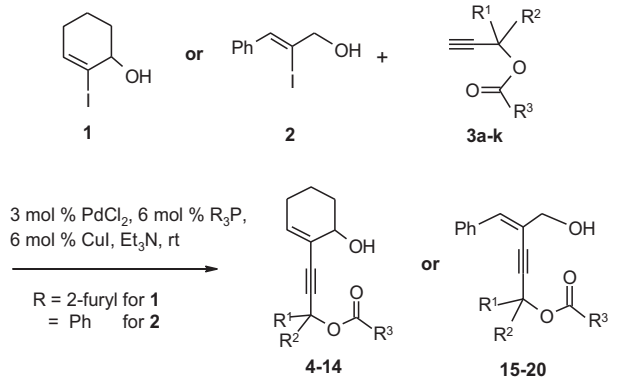
Although activation of allenes by Au^{I}/Au^{III} is described earlier, many of these result in five-membered ring formation[12] and only in a few cases, 6-*endo-trig* cyclisation is observed.[13] Very recently, work on racemic phenolic propargylic esters using gold(I)–chiral acyclic diaminocarbene complex for excellent chirality transfer is reported by Toste's group.[14] We were also interested to apply Au(I) catalysis using simpler ligands. Thus, as a useful and convenient variation, herein we report gold(I) catalysed efficient cycloisomerisation of our multifunctional β-hydroxy propargylic esters **4**–**20** and **24** [obtained easily using iodo alcohols **1**–**2** and propargylic esters **3a**–**k**] to dihydropyrans/*H*-pyrans via regioselective 6-*endo-trig* cyclisation. The applicability of this pyran formation protocol is then compared/contrasted with that of furan formation by analogous phosphorus based substrates.[4e]

2. Results and discussion

2.1. Synthesis of propargylic ester precursors 4–24

2-Iodo-cyclohex-2-enol **1** and 2-iodo-cinnamyl alcohol **2** were coupled with terminal propargylic esters **3a**–**k** for the synthesis of β-hydroxy propargylic esters (2-alkynyl allylic alcohols) **4**–**20**. In the case of 2-iodo-cyclohex-2-enol, the phosphine Ph_3P was not effective and hence $(2\text{-furyl})_3P$[15] had to be used as the phosphine component (Scheme 2, Table 1). Compounds **21**–**23** were synthesised starting from 2-iodo-cinnamaldehyde[16] and propargylic esters **3b**–**d** (Scheme 3). The hydroxy propargylic ester **24** was obtained by treating **22** with methyllithium.

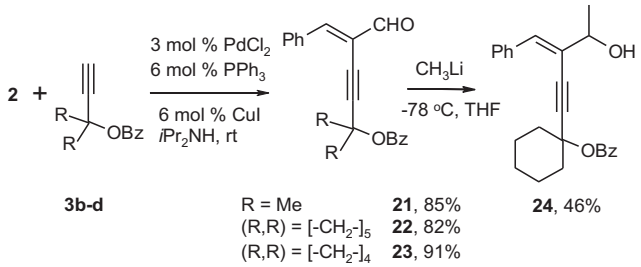


Scheme 2. Synthesis of β-hydroxy propargylic esters **4**–**20**.

Table 1
Details on the synthesis of β-hydroxy propargylic esters **4**–**20**

Entry	Iodo-alcohol	Propargylic ester	Product, Yield[a]
1	**1**	R^1=R^2=H, R^3=Ph (**3a**)	**4**, 70%
2	**1**	R^1=R^2=Me, R^3=Ph (**3b**)	**5**, 86%
3	**1**	(R^1,R^2)=[$-CH_2-$]$_5$, R^3=Ph (**3c**)	**6**, 81%
4	**1**	(R^1,R^2)=[$-CH_2-$]$_4$, R^3=Ph (**3d**)	**7**, 76%
5	**1**	R^1=Me, R^2=Et, R^3=Ph (**3e**)	**8**, 81%
6	**1**	R^1=R^2=Me, R^3=Me (**3f**)	**9**, 80%
7	**1**	(R^1,R^2)=[$-CH_2-$]$_5$, R^3=Me (**3g**)	**10**, 62%
8	**1**	R^1=R^2=Me, R^3=Et (**3h**)	**11**, 84%
9	**1**	R^1=Me, R^2=*i*-Bu, R^3=Ph (**3i**)	**12**, 66%
10	**1**	R^1=Me, R^2=*n*-pentyl, R^3=Ph (**3j**)	**13**, 72%
11	**1**	R^1=R^2=*n*-propyl, R^3=Ph (**3k**)	**14**, 73%
12	**2**	R^1=R^2=H, R^3=Ph (**3a**)	**15**, 82%
13	**2**	R^1=R^2=Me, R^3=Ph (**3b**)	**16**, 84%
14	**2**	(R^1,R^2)=[$-CH_2-$]$_5$, R^3=Ph (**3c**)	**17**, 88%
15	**2**	(R^1,R^2)=[$-CH_2-$]$_4$, R^3=Ph (**3d**)	**18**, 81%
16	**2**	R^1=Me, R^2=Et, R^3=Ph (**3e**)	**19**, 82%
17	**2**	R^1=R^2=Me, R^3=Me (**3f**)	**20**, 92%

[a] Yield of the isolated product.

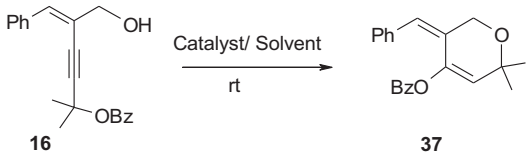


Scheme 3. Synthesis of α-formyl propargylic esters **21**–**23** and β-hydroxy propargylic ester **24**.

2.2. Cycloisomerisation of β-hydroxy propargylic esters

In the cycloisomerisation of compounds **4**–**20** and **24** leading to pyran derivatives **25**–**42**, initial trials were performed on **16** by treating it with 2 mol % $Ph_3PAuCl/AgOTf$ in dichloromethane (Table 2). To our delight, the reaction using **16** led to **37** in 82% yield of the isolated product (entry 1). Use of $AgBF_4$ (entry 2) in place of AgOTf reduced the time for completion of reaction from 6 h to 4 h and increased the yield to 84%. By employing $AgSbF_6$ as additive, the reaction time was further reduced to 1 h and concomitantly, the yield was still higher (90%; entry 3). In the absence of silver additives, no product formation was observed even after 12 h; AuCl or $AuCl_3$ as the gold component afforded lower yields after 12 h with some starting material (~25%) remaining (entries 5 and 6). In the absence of gold catalyst, $AgSbF_6$ or $AgBF_4$ (5 mol %) gave the product in 78% or 68% yield (entries 7 and 8), respectively, in 6 h, whereas AgOTf did not work well (entry 9). Other catalytic systems were also less effective. Solvents like CH_3CN, toluene, THF and dioxane along with 2% $Ph_3PAuCl/AgSbF_6$ led to poor yields (entries 13–16). Thus 2% $Ph_3PAuCl/AgSbF_6$ catalytic system in CH_2Cl_2 as the solvent was the best condition (entry 3).

Table 2
Effect of catalyst/solvent in cycloisomerisation of **16**



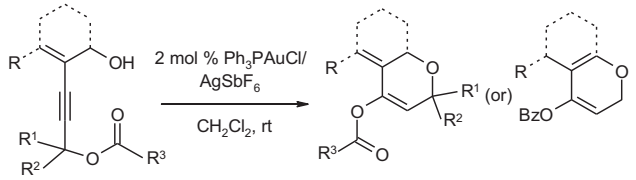
Entry	Catalyst (mol %)	Solvent	Time (h)	Yield %[a]
1	2% $Ph_3PAuCl/AgOTf$	CH_2Cl_2	6	82
2	2% $Ph_3PAuCl/AgBF_4$	CH_2Cl_2	4	84
3	2% $Ph_3PAuCl/AgSbF_6$	CH_2Cl_2	1	90
4	2% Ph_3PAuCl	CH_2Cl_2	12	No reaction[b]
5	2% AuCl	CH_2Cl_2	12	Trace[b]
6	2% $AuCl_3$	CH_2Cl_2	12	52[b]
7	5% $AgSbF_6$	CH_2Cl_2	6	78
8	5% $AgBF_4$	CH_2Cl_2	6	68
9	5% AgOTf	CH_2Cl_2	12	18[b]
10	2% $AuCl_3/AgSbF_6$	CH_2Cl_2	1	Complex mixture
11	2% $AuCl/AgSbF_6$	CH_2Cl_2	12	42[b]
12	1% $Ph_3PAuCl/AgSbF_6$	CH_2Cl_2	5	76
13	2% $Ph_3PAuCl/AgSbF_6$	Dioxane	12	10[b]
14	2% $Ph_3PAuCl/AgSbF_6$	THF	12	Trace[b]
15	2% $Ph_3PAuCl/AgSbF_6$	Toluene	12	20[b]
16	2% $Ph_3PAuCl/AgSbF_6$	CH_3CN	12	Trace[b]

[a] Yield of the isolated product.
[b] Starting material remained.

The generality of the above reaction was checked against different substitutions on β-hydroxy propargylic esters. The precursors **4**–**20** were successfully cycloisomerised to pyran derivatives **25**–**41** (Table 3), respectively, in 64–90% yield.

Similarly, precursor **24** (Table 3, entry 18) led to dihydropyran **42** in 86% yield. Among these products, **25** and **36** are 2*H*-pyrans, which are synthesised from unsubstituted benzoates **4** and **15** (entries 1 and 12), whereas the rest are dihydropyrans. The structure of the dihydropyran **27** was confirmed by X-ray crystallography (Fig. 1).

Table 3
Details on cycloisomerisation of β-hydroxy propargylic esters (**4**–**20** and **24**) to pyran derivatives **25**–**42**



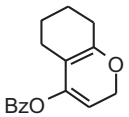
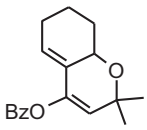
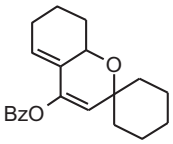
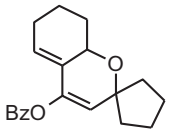
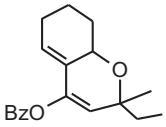
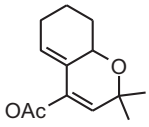
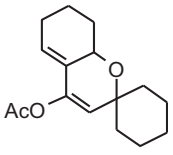
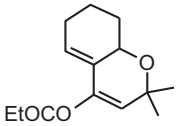
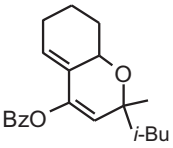
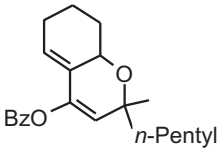
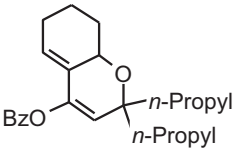
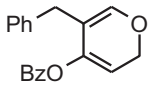
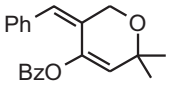
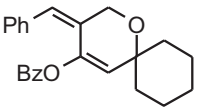
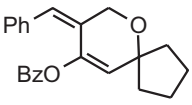
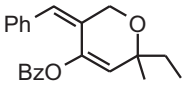
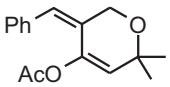
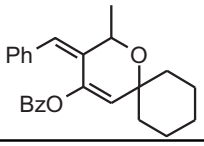
Entry	Substrate	Product, Yield[a]
1	**4**	 **25**, 75%
2	**5**	 **26**, 72%
3	**6**	 **27**, 65% X-ray
4	**7**	 **28**, 78%
5[b]	**8**	 **29**, 80%
6	**9**	 **30**, 75%
7	**10**	 **31**, 78%
8	**11**	 **32**, 73%
9[b]	**12**	 **33**, 78%

Table 3 (*continued*)

Entry	Substrate	Product, Yield[a]
10[b]	**13**	 **34**, 82%
11	**14**	 **35**, 81%
12	**15**	 **36**, 64%
13	**16**	 **37**, 90%
14	**17**	 **38**, 82%
15	**18**	 **39**, 86%
16	**19**	 **40**, 64%
17	**20**	 **41**, 74%
18	**25**	 **42**, 86%

[a] Yield of the isolated product.
[b] Mixture of diastereomers.

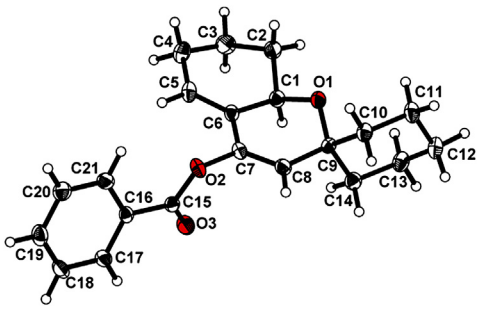
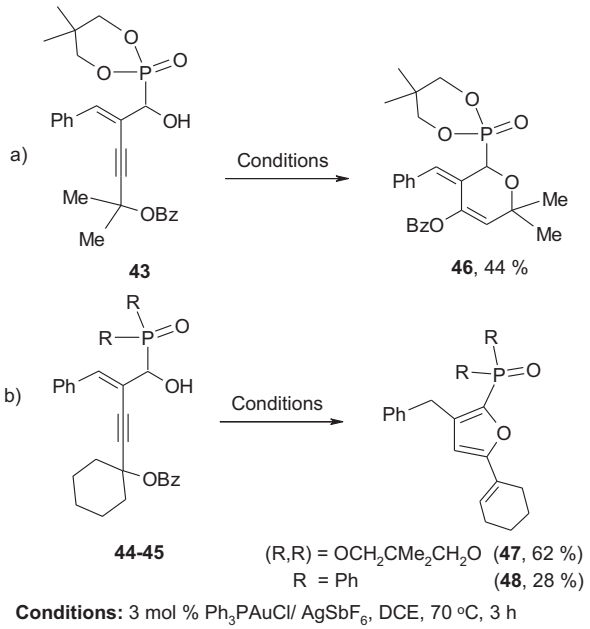


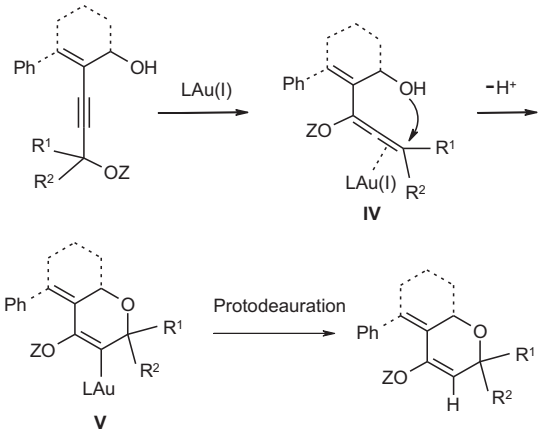
Fig. 1. ORTEP of compound **27**. Selected bond lengths [Å] with esd's in parentheses: O1–C9 1.433(3), C7–C8 1.318(3), O2–C7 1.411(3).

Our success in the above cycloisomerisation prompted us to check the synthesis of phosphorus containing oxacycles.[17] For this purpose, we prepared (hydroxy)phosphonates[18] **43**–**45** from α-formyl propargyl esters **21**–**22**. Although these phosphono-alkynols when treated with 3% $Ph_3PAuCl/AgSbF_6$ in dichloroethane did not react at 25 °C, the reaction was complete in 3 h when heated at 70 °C.[4e] Precursor **43** led to phosphono-pyran **46** (Scheme 4a), whereas **44** and **45** led to phosphono-furan **47** and phosphinoyl furan **48**, respectively (Scheme 4b). However, the yields in these cases are quantitative according to ^{31}P NMR. Additional peaks corresponding to phosphorus containing furans/pyrans were observed, but these products were not isolated. It is to be noted that in the phosphono-furans, the benzoyloxy group has been eliminated as benzoic acid leading to the cycloalkenic double bond at the corresponding site. Thus an interesting variation in the product formation is observed with these phosphono-alkynol precursors.[19]



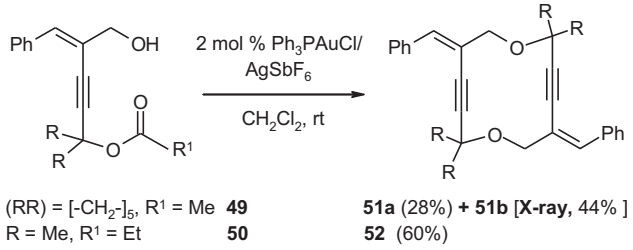
Scheme 4. Synthesis and cyclisation of phosphono-alkynols to phosphono-furans or phosphono-pyrans.

We propose that the reaction leading to pyrans proceeds via Au(I) catalysed π-activation of propargylic ester, which undergoes 1,3-carboxylate migration[11] to form allene intermediate **IV** (Scheme 5) followed by regioselective hydroxyl group addition to allene, which is 6-*endo*-*trig* cyclisation affording the six-membered oxacycle **V**. Subsequently, **V** undergoes proto-deauration to lead to pyran derivative.[11,14] The reaction also occurs with silver salts, albeit less effectively, due to the strong electron withdrawing nature (of the groups) in counter anions. The softness of silver also plays a role in coordinating with the alkyne moiety and hence an Ag(I) intermediate similar to **IV**–**V** is feasible.[1c] With regard to the cycloisomerisation of phosphono-alkynols to *phosphono-pyrans*, the reaction pathway is analogous to the above, whereas the formation of *phosphono-furans* has occurred differently.[4e] The reason for the difference in reactivity between the non-phosphorus alkynols and phosphorus-containing alkynols is probably a consequence of the electron withdrawing nature of the phosphoryl group.



Scheme 5. Proposed reaction pathway for the formation of pyran.

There appears to be some subtle steric/electronic factors involved here. We found that β-hydroxy propargylic esters **49**–**50** underwent self-condensation via nucleophilic substitution[20] of ester group to afford 12-membered macrocycles **51**(**a**,**b**)–**52**, respectively (Scheme 6). The isomerism may be due to the different conformations (or disposition of substituents) of the cyclohexyl rings in **51a**,**b**; such a possibility does not arise in the case of **52**. In the absence of the catalyst, the reaction using **49** did not give the cyclised products **51a**,**b**. In addition to the steric/electronic factors, perhaps, the oxophilicity of gold(I) complex[20c,d] might have driven the condensation. Two isomers **51a**,**b** were formed (and separated) in the reaction using **49**, the geometry of **51b** was confirmed by X-ray crystallography (Fig. 2). These products could be attractive substrates for cycloaddition reactions. Although this condensation is interesting, it is not the main theme of the present work and hence is not elaborated in this study.



Scheme 6. Formation of macrocycles from β-hydroxy propargylic esters.

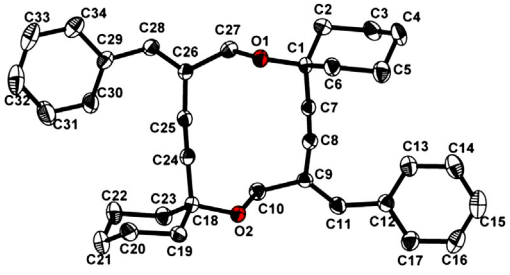


Fig. 2. ORTEP of compound **51b**. Selected bond lengths [Å] with esd's in parentheses: (Hydrogens are omitted for clarity) O1–C1 1.437(3) and O2–C18 1.443(3).

3. Conclusions

In summary, various pyran derivatives have been synthesised from β-hydroxy propargylic esters via 1,3-carboxylate migration (leading to allenic intermediates) followed by regioselective cyclisation. The method utilises a wide range of easily accessible precursors, and demonstrates general and highly efficient route for a variety of substituted pyrans under mild conditions in short reaction time. Phosphorus containing hydroxy propargyl esters led to *phosphono-furans* as well as *phosphono-pyrans* under the same catalytic system. During this investigation it is also shown that, in a few cases, the electronic factors compelled the dimerisation of propargylic esters via nucleophilic substitution to form 12-membered macrocycles, indicating a different reactivity pattern of the precursors.

4. Experimental section

4.1. General

Solvents were dried according to known methods as appropriate.[21] ^{1}H, ^{13}C and ^{31}P NMR spectra (^{1}H, 400 MHz; ^{13}C, 100.6 MHz; ^{31}P, 162 MHz) were recorded using a 400 MHz spectrometer in $CDCl_3$ with shifts referenced to $SiMe_4$ (δ 0) or 85% H_3PO_4 (δ 0). IR spectra were recorded on an FTIR spectrophotometer. Melting points were determined by using a local hot-stage melting point apparatus and are uncorrected. Elemental analyses were carried out on a Perkin–Elmer 240C CHN or Thermo Finnigan EA1112 CHNS analyzer from School of Chemistry, University of Hyderabad, Hyderabad. Mass spectra were recorded using LC/MS and HRMS (ESI-TOF analyzer) equipment.

Precursors **1**,[22] **2**[4e,16] and **3a**–**g**[3j–l,23] are known.

4.2. Synthesis of propargylic esters 3h–k

*4.2.1. 2-Methylbut-3yn-2yl propionate **3h**.* This compound was synthesised by following a literature procedure[24a] by using 2-methylbut-3-yn-2ol (0.864 g, 10.3 mmol), propionyl chloride (1.80 mL, 20.6 mmol), DMAP (0.379 g, 3.1 mmol) and pyridine (8.3 mL) in CH_2Cl_2 (40 mL). Yield 1.44 g (85%); Colourless oil; [Found: C, 68.54; H, 8.63. $C_8H_{12}O_2$ requires C, 68.46; H, 8.71%]; IR (neat, cm^{-1}) 3293, 3058, 2986, 2937, 2290, 2247, 1734, 1425, 1266, 1195, 1134, 1085, 1041; δ_H (400 MHz, $CDCl_3$) 2.53 (1H, s), 2.30 (2H, qrt, J=7.8 Hz), 1.67 (6H, s), 1.13 (3H, t, J=7.4 Hz); δ_C (100.6 MHz, $CDCl_3$) δ 172.5, 84.7, 72.1, 71.2, 28.8, 28.0, 8.8; LC/MS m/z 141 $[M+1]^+$.

*4.2.2. 3,5-Dimethylhex-1-yn-3-yl benzoate **3i**.* This compound was obtained by desilylation of **VI** (see Supplementary data) (1.40 g, 4.6 mmol) using a literature procedure.[24b] Yield 0.953 g (90%, colourless oil). The spectral data are in accordance with the literature report.[3h]

*4.2.3. 3-Methyloct-1-yn-3yl benzoate **3j**.* This compound was obtained by desilylation **VII** (2.00 g, 6.3 mmol) in a manner similar to that for **3i**. Yield 1.37 g (89%); Colourless oil; R_f (2% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3304, 3260, 2953, 2932, 2871, 2121, 1726, 1606, 1447, 1375, 1271, 1178, 1156, 1107, 1074, 1030, 882, 718; δ_H (400 MHz, $CDCl_3$) 8.03–7.42 (5H, m), 2.61 (1H, s), 2.11–1.95 (2H, m), 1.82 (3H, s), 1.65–1.57 and 1.38–1.35 (6H, m), 0.93 (3H, t, J=6.8 Hz); δ_C (100.6 MHz, $CDCl_3$) 164.9, 1361, 132.9, 131.0, 129.6, 128.4, 84.0, 75.6, 73.5, 41.7, 31.8, 26.6, 23.9, 22.6, 14.1; HRMS (ESI): $[M^+$+Na], found 267.1362. $C_{16}H_{20}NaO_2$ requires 267.1361.

*4.2.4. 4-Ethynylheptan-4-yl benzoate **3k**.* This compound was obtained by desilylation **VIII** (2.00 g, 6.3 mmol) as described for **3i**. Yield 1.33 g (86%); Colourless oil; [Found: C, 78.76; H, 8.15. $C_{16}H_{20}O_2$ requires C, 78.65; H, 8.25%]; R_f (2% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3304, 3069, 2959, 2932, 2877, 2121, 1726, 1606, 1447, 1277, 1118, 1096, 1025, 948, 712; δ_H (400 MHz, $CDCl_3$) 8.03–7.42 (5H, m), 2.62 (1H, s), 2.17–2.12 and 2.04–1.98 (4H, m), 1.61–1.53 (4H, m), 0.98 (3H, t, J=7.4 Hz); δ_C (100.6 MHz, $CDCl_3$) 164.7, 132.8, 130.9, 129.5, 128.3, 83.3, 79.0, 74.2, 40.6, 17.4, 14.1; LC/MS m/z 245 $[M+1]^+$.

4.3. Synthesis of β-hydroxy propargylic esters 4–14

The procedure available in the literature[4b] was modified in this case. To a mixture of 2-iodocyclohex-2-enol (**1**) (400 mg, 1.80 mmol), $PdCl_2$ (10 mg, 0.03 mol equiv), $(furyl)_3P$ (25 mg, 0.06 equiv) and CuI (21 mg, 0.06 equiv) in triethylamine (6 mL) was added the appropriate alkyne among **3a**–**k** (2.4 mmol, 1.5 equiv) through a micropipette. The contents were stirred for 6 h at rt. The reaction mixture was filtered and the solvent removed in vacuum. The crude product was purified by column chromatography using silica gel with EtOAc/hexane mixture as the eluent.

*4.3.1. 3-(6-Hydroxycyclohex-1-enyl)prop-2-ynyl benzoate **4**.* Yield 0.325 g (70%); Gummy liquid; [Found: C, 74.85; H, 6.21. $C_{16}H_{16}O_3$ requires C, 74.98; H, 6.29%]; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3443, 3061, 2946, 2870, 2300 (w), 2230, 1728, 1603, 1580, 1453, 1271, 1109, 739; δ_H (400 MHz, $CDCl_3$) 8.08–7.42 (5H, m), 6.29 (1H, t, J=4.0 Hz), 5.06 (2H, s), 4.19 (1H, br s), 2.19–1.57 (6H, m); δ_C (100.6 MHz, $CDCl_3$) 166.0, 139.1, 133.3, 129.8, 129.5, 128.3, 123.3, 85.9, 82.8, 66.6, 53.4, 30.6, 25.9, 17.9; LC/MS m/z 257 $[M+1]^+$.

*4.3.2. 4-(6-Hydroxycyclohex-1-enyl)-2-methylbut-3-yn-2-yl benzoate **5**.* Yield 0.437 g (86%); Gummy liquid; [Found: C, 76.13; H, 7.15. $C_{18}H_{20}O_3$ requires C, 76.03; H, 7.09%]; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3470, 3063, 2986, 2940, 2868, 2300 (vw), 2220 (w), 1719, 1603, 1584, 1283, 1107, 714; δ_H (400 MHz, $CDCl_3$) 8.03–8.01 and 7.56–7.40 (5H, m), 6.16 (1H, t, J=3.8 Hz), 4.21–4.20 (1H, m), 2.11–1.96 (2H, m), 1.82 (6H, s), 1.79–1.55 (4H, m); δ_C (100.6 MHz, $CDCl_3$) 165.4, 136.5, 132.9, 130.9, 129.7, 128.3, 124.4, 91.1, 83.6, 73.1, 67.2, 30.3, 29.2, 29.0, 25.8, 19.0; LC/MS m/z 285 $[M+1]^+$.

*4.3.3. 1-((6-Hydroxycyclohex-1-enyl)ethynyl)cyclohexyl benzoate **6**.* Yield 0.473 g (81%); Gummy liquid; [Found: C, 77.63; H, 7.36. $C_{21}H_{24}O_3$ requires C, 77.75; H, 7.46%]; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3519, 2936, 2861, 2218, 1721, 1601, 1451, 1283, 1250, 1109, 914, 712; δ_H (400 MHz, $CDCl_3$) 8.05–7.41 (5H, m), 6.17 (1H, t, J=4.2 Hz), 4.20 (1H, t, J=5.4 Hz), 1.98–2.21 and 1.45–1.80 (16H, m); δ_C (100.6 MHz, $CDCl_3$) 165.2, 136.4, 132.9, 131.1, 129.7, 128.3, 124.6, 90.3, 85.3, 76.5, 67.3, 37.3, 30.3, 25.8, 25.2, 22.6, 19.1; LC/MS m/z 325 $[M+1]^+$.

*4.3.4. 1-((6-Hydroxycyclohex-1-enyl)ethynyl)cyclopentyl benzoate **7**.* Yield 0.426 g (76%); Gummy liquid; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3467, 2939, 2867, 2215, 1950 (w), 1713, 1599, 1444, 1273, 1164, 1102, 962, 709; δ_H (400 MHz, $CDCl_3$) 8.02–7.40 (5H, m), 6.15 (1H, t, J=4.0 Hz), 4.19 (1H, t, J=6.2 Hz), 2.44–2.41, 2.27–2.01, 1.99–1.93, 1.85–1.72 and 1.67–1.55 (14H, m); δ_C (100.6 MHz, $CDCl_3$) 165.6, 136.5, 133.0, 130.0, 129.7, 128.3, 124.5, 90.3, 84.2, 81.8, 67.1, 40.6, 30.3, 25.8, 23.5, 18.9; HRMS (ESI): $[M^+$+Na], found 333.1466. $C_{20}H_{22}NaO_3$ requires 333.1467.

*4.3.5. 1-(6-Hydroxycyclohex-1-enyl)-3-methylpent-1-yn-3-yl benzoate **8**: (mixture of diastereomers).* Yield 0.435 g (81%); Gummy liquid; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3482, 2980, 2933, 2876, 2213, 1721, 1447, 1281, 1105, 1022, 717; δ_H (400 MHz, $CDCl_3$) 8.03–7.41 (10H, m), 6.17 (2H, br s), 4.23 and 4.19 (2H, two br s), 3.13 (2H, s), 2.15–1.81 and 1.76–1.54 (22H, m), 1.15–1.10 (6H, m); δ_C (100.6 MHz, $CDCl_3$) 165.5, 165.3, 136.5, 136.2, 132.9, 131.0, 129.6,

128.3, 124.5, 90.0, 84.7, 76.8, 67.3, 67.2, 34.9, 34.7, 30.3, 26.3, 25.8, 19.0, 8.8; HRMS (ESI): [M^++Na], found 321.1465. $C_{19}H_{22}NaO_3$ requires 321.1467.

4.3.6. 4-(6-Hydroxycyclohex-1-enyl)-2-methylbut-3-yn-2-yl acetate ***9***. Yield 0.320 g (80%); Gummy liquid; [Found: C, 70.15; H, 8.23. $C_{13}H_{18}O_3$ requires C, 70.24; H, 8.16%]; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3470, 2988, 2940, 2870, 2300 (vw), 2224, 1734, 1672, 1368, 1271, 1244, 1129, 1017; δ_H (400 MHz, $CDCl_3$) 6.15 (1H, t, J=3.8 Hz), 4.17 (1H, t, J=6.2 Hz), 2.86 (1H, br s), 2.13–2.08 (2H, m), 1.99–1.93 and 1.79–1.72 (2H, m), 2.02 (3H, s), 1.66 (6H, s), 1.65–1.62 (2H, m); δ_C (100.6 MHz, $CDCl_3$) 169.9, 136.5, 124.3, 90.9, 83.2, 72.4, 67.0, 30.2, 29.0, 28.8, 25.7, 22.0, 18.8; LC/MS m/z 223 $[M+1]^+$.

4.3.7. 1-((6-Hydroxycyclohex-1-enyl)ethynyl)cyclohexyl acetate ***10***. Yield 0.294 g (62%); Gummy liquid; [Found: C, 73.16; H, 8.35. $C_{16}H_{22}O_3$ requires C, 73.25; H, 8.45%]; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3468, 2938, 2863, 2218, 1740, 1768, 1449, 1269, 1233, 1020; δ_H (400 MHz, $CDCl_3$) 6.16 (1H, t, J=4.0 Hz), 4.18 (1H, t, J=6.4 Hz), 2.90 (1H, br s), 2.13–2.07 (4H, m), 2.04 (3H, s), 1.84–1.28 (12H, m); δ_C (100.6 MHz, $CDCl_3$) 169.9, 136.3, 124.6, 90.2, 85.1, 76.0, 67.3, 37.2, 37.0, 30.3, 25.8, 25.2, 22.7, 22.1, 19.0; LC/MS m/z 263 $[M+1]^+$.

4.3.8. 4-(6-Hydroxycyclohex-1-enyl)-2-methylbut-3-yn-2-yl propionate ***11***. Yield 0.360 g (84%); Gummy liquid; [Found: C, 71.23; H, 8.45. $C_{14}H_{20}O_3$ requires C, 71.16; H, 8.53%]; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3478, 2986, 2942, 2874, 2350 (w), 2220, 1732, 1628, 1462, 1362, 1275, 1190, 1129, 1080, 997; δ_H (400 MHz, $CDCl_3$) 6.14 (1H, t, J=4.0 Hz), 4.17 (1H, br s), 2.95 (1H, br s), 2.29 (2H, qrt, J=7.6 Hz), 2.11–1.68 (12H, m), 1.11 (3H, t, J=7.4 Hz); δ_C (100.6 MHz, $CDCl_3$) 173.6, 136.4, 124.5, 91.3, 83.1, 72.2, 67.2, 30.3, 29.1, 28.9, 28.4, 25.8, 19.0, 9.0; LC/MS m/z 237 $[M+1]^+$.

4.3.9. 1-(6-Hydroxycyclohex-1-enyl)-3,5-dimethylhex-1-yn-3-yl benzoate ***12*** *(two diastereomers).* Yield 0.385 g (66%); Gummy liquid; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3485, 3069, 2959, 2850, 2219, 1710, 1606, 1452, 1277, 1107, 1025, 712; δ_H (400 MHz, $CDCl_3$) 8.02–8.00 and 7.57–7.40 (10H, m), 6.17–6.14 (2H, m), 4.23 and 4.18 (2H, two t, J=6.2 and 6.0 Hz, respectively), 3.13 (2H, br s), 2.13–1.96, 1.90–1.74 and 1.66–1.61 (24H, m), 1.03–1.09 (12H, m); δ_C (100.6 MHz, $CDCl_3$) 165.6, 165.4, 136.6, 136.2, 133.0, 131.0, 130.2, 129.7, 128.5, 128.4, 124.4, 90.4, 84.9, 76.4, 67.2, 50.0, 49.8, 30.2, 27.5, 27.3, 25.8, 25.1, 24.2, 24.1, 19.0; HRMS (ESI): [M^++Na], found 349.1780. $C_{21}H_{26}NaO_3$ requires 349.1780.

4.3.10. 1-(6-Hydroxycyclohex-1-enyl)-3-methyloct-1-yn-3-yl benzoate ***13*** *(two diastereomers).* Yield 0.438 g (72%); Gummy liquid; [Found: C, 77.52; H, 8.15. $C_{22}H_{28}O_3$ requires C, 77.61; H, 8.29%]; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3493, 3058, 2939, 2867, 2215, 1713, 1604, 1449, 1273, 1107, 1024, 719; δ_H (400 MHz, $CDCl_3$) 8.01–7.27 (10H, m), 6.17 and 6.16 (2H, two br s), 4.23 and 4.18 (2H, two br s), 2.10–1.90, 1.80–1.74 and 1.64–1.54 (26H, m), 1.36 (8H, br s), 0.92 (6H, br s); δ_C (100.6 MHz, $CDCl_3$) 165.5, 165.4, 136.6, 136.2, 132.9, 131.0, 129.7, 128.3, 124.5, 90.3, 84.6$_1$, 84.6$_0$, 76.8, 76.4, 67.3, 67.2, 41.8, 41.6, 31.8, 30.2, 26.8$_0$, 26.7$_5$, 25.8, 24.0$_3$, 24.0$_0$, 22.6, 19.0, 14.1; LC/MS m/z 341 $[M+1]^+$.

4.3.11. 4-((6-Hydroxycyclohex-1-enyl)ethynyl)heptan-4-yl benzoate ***14***. Yield 0.445 g (73%); Gummy liquid; R_f (20% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3485, 2970, 2926, 2866, 2214, 1715, 1606, 1452, 1277, 1112, 1025, 712; δ_H (400 MHz, $CDCl_3$) 8.01–7.40 (5H, m), 6.16 (1H, t, J=3.6 Hz), 4.21 (1H, br s), 3.16 (1H, br s), 2.14–1.95 and 1.78–1.48 (14H, m), 0.98 (6H, t, J=7.0 Hz); δ_C (100.6 MHz, $CDCl_3$) 165.4, 136.2, 132.9, 131.1, 129.7, 128.4, 124.6, 89.6, 85.5, 79.7, 67.3, 41.0, 40.9, 30.3, 25.8, 19.1, 17.7$_0$, 17.6$_5$, 14.3; HRMS (ESI): [M^++Na], found 363.1937. $C_{22}H_{28}NaO_3$ requires 363.1936.

4.4. Synthesis of β-hydroxy propargylic esters 15–20

A literature procedure[4b] was slightly modified. To a mixture of (*Z*)-2-iodo-3-phenylprop-2-en-1ol **2** (400 mg, 1.54 mmol), $PdCl_2$ (8 mg, 0.03 mol equiv), PPh_3 (21 mg, 0.06 mol equiv) and CuI (18 mg, 0.06 mol equiv) in triethylamine (5 mL) was added the appropriate alkyne among **3a**–**f** (1.5 equiv). The contents were stirred for 6 h at rt. The reaction mixture was filtered and the solvent removed in vacuum. The crude product was purified by column chromatography using silica gel with EtOAc/hexane (1:5) mixture as eluent.

4.4.1. (E)-4-(Hydroxymethyl)-5-phenylpent-4-en-2-ynyl benzoate ***15***. Yield 0.369 g (82%); Gummy liquid; [Found: C, 77.93; H, 5.61. $C_{19}H_{16}O_3$ requires C, 78.06; H, 5.52%]; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3439, 3063, 3030, 2928, 2859, 2216, 1725, 1601, 1493, 1451, 1269, 1107, 758, 712; δ_H (400 MHz, $CDCl_3$) 8.12–7.29 (10H, m), 6.84 (1H, s), 5.17 (1H, s), 4.32 (1H, s); δ_C (100.6 MHz, $CDCl_3$) 166.0, 135.6, 135.5, 133.4, 129.9, 129.6, 128.8, 128.6, 128.5, 128.4, 120.3, 90.9, 84.6, 67.1, 53.5; LC/MS m/z 293 $[M+1]^+$.

4.4.2. (E)-5-(Hydroxymethyl)-2-methyl-6-phenylhex-5-en-3-yn-2-yl benzoate ***16***. Yield 0.414 g (84%); Gummy liquid; [Found: C, 78.65; H, 6.36. $C_{21}H_{20}O_3$ requires C, 78.73; H, 6.29%]; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3434, 3063, 3027, 2986, 2934, 2865, 2207, 1968, 1723, 1451, 1281, 1105, 1026, 756, 714, 693; δ_H (400 MHz, $CDCl_3$) 8.06–7.28 (10H, m), 6.73 (1H, s), 4.29 (2H, s), 2.53 (1H, s), 1.90 (6H, s); δ_C (100.6 MHz, $CDCl_3$) 165.3, 135.8, 134.1, 133.1, 130.8, 129.7, 128.7, 128.4, 128.2, 121.1, 98.4, 82.5, 73.1, 67.3, 29.0; LC/MS m/z 321 $[M+1]^+$.

4.4.3. (E)-1-(3-(Hydroxymethyl)-4-phenylbut-3-en-1-ynyl)cyclohexyl benzoate ***17***. Yield 0.488 g (88%); Gummy liquid; [Found: C, 79.85; H, 6.63. $C_{24}H_{24}O_3$ requires C, 79.97; H, 6.71%]; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3468, 3068, 3025, 2931, 2860, 2197, 1704, 1600, 1452, 1288, 1184, 1118, 1074, 910, 756, 707; δ_H (400 MHz, $CDCl_3$) 8.08–7.24 (10H, m), 6.72 (1H, s), 4.29 (2H, s), 2.72 (1H, s), 2.35–2.12 (4H, m), 1.77–1.45 (6H, m); δ_C (100.6 MHz, $CDCl_3$) 165.1, 135.8, 133.6, 133.0, 130.8, 129.6, 128.6, 128.3, 128.2, 128.1, 121.3, 97.5, 84.3, 76.5, 67.1, 37.0, 25.1, 22.6; LC/MS m/z 361 $[M+1]^+$.

4.4.4. (E)-1-(3-(Hydroxymethyl)-4-phenylbut-3-en-1-ynyl)cyclopentyl benzoate ***18***. Yield 0.435 g (81%); Gummy liquid; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3436, 3063, 2960, 2867, 2220 (w), 1980 (w), 1718, 1599, 1444, 1278, 1107, 1030; δ_H (400 MHz, $CDCl_3$) 8.04–7.24 (10H, m), 6.72 (1H, s), 4.28 (2H, s), 2.51–2.31 and 1.89–1.85 (8H, m), 1.02 (1H, t, J=7.2 Hz); δ_C (400 MHz, $CDCl_3$) 165.5, 135.8, 133.9, 133.1, 130.6, 129.7, 128.6, 128.4, 128.3, 128.2, 121.3, 97.7, 83.1, 81.7, 67.2, 40.4, 23.5; HRMS (ESI): [M^++Na], found 369.1466. $C_{23}H_{22}NaO_3$ requires 369.1467.

4.4.5. (E)-6-(Hydroxymethyl)-3-methyl-7-phenylhept-6-en-4-yn-3-yl benzoate ***19***. Yield 0.440 g (82%); Gummy liquid; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3446, 3058, 2970, 2934, 2877, 2220 (w), 1723, 1495, 1444, 1268, 1107, 1066, 1024, 714; δ_H (400 MHz, $CDCl_3$) 8.06–7.26 (10H, m), 6.72 (1H, s), 4.30 (2H, s), 2.62 (1H, s), 2.23–2.03 (2H, m), 1.88 (3H, s), 1.17 (1H, t, J=7.4 Hz); δ_C (100.6 MHz, $CDCl_3$) 165.3, 135.8, 133.9, 133.0, 130.9, 129.6, 128.6, 128.4, 128.3, 128.2, 121.3, 97.5, 83.6, 76.8, 67.3, 34.7, 26.1, 8.8; HRMS (ESI): [M^++Na], found 357.1468. $C_{22}H_{22}NaO_3$ requires 357.1467.

4.4.6. (E)-5-(Hydroxymethyl)-2-methyl-6-phenylhex-5-en-3-yn-2-yl acetate ***20***. Yield 0.368 g (92%); Gummy liquid; [Found: C, 74.21; H,

7.13. $C_{16}H_{18}O_3$ requires C, 74.39; H, 7.02%]; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3426, 3058, 3025, 2988, 2936, 2865, 2215, 1740, 1600, 1495, 1447, 1368, 1244, 1129, 1019, 756, 694; δ_H (400 MHz, $CDCl_3$) 7.83–6.72 (6H, m), 4.27 (1H, s), 2.06 (3H, s), 1.74 (6H, s); δ_C (100.6 MHz, $CDCl_3$) 169.9, 135.8, 134.0, 128.6, 128.3, 128.1, 121.1, 98.2, 82.1, 72.4, 67.0, 28.8, 22.0; LC/MS *m*/*z* 259 $[M+1]^+$.

4.5. Synthesis of α-formyl propargylic esters 21–23

A literature procedure[4b] was modified. To a mixture of (*Z*)-2-iodo-3-phenyl acraldehyde[16] (500 mg, 1.94 mmol), $PdCl_2$ (10 mg, 0.03 mol equiv), $(furyl)_3P$ (28 mg, 0.06 mol equiv), CuI (23 mg, 0.06 mol equiv) and diisopropylamine (0.9 mL, 3.0 mol equiv) in THF (6 mL) was added the corresponding alkyne **3b–d** (1.5 mol equiv). The contents were stirred for 6 h at rt. The reaction mixture was filtered and the solvent removed by vacuum. The crude product was purified by column chromatography using silica gel with EtOAc/hexane mixture as eluent.

4.5.1. (E)-5-Formyl-2-methyl-6-phenylhex-5-en-3-yn-2-yl benzoate ***21***. Yield 0.525 g (85%); White solid; Mp 64–66 °C; R_f (10% EtOAc/hexane) 0.35; IR (KBr, cm^{-1}) 3069, 2981, 2833, 2250 (vw), 1726, 1682, 1589, 1452, 1277, 1145, 1096, 910, 712, 690; δ_H (400 MHz, $CDCl_3$) 9.57 (1H, s), 8.13–7.37 (11H, m), 1.96 (6H, s); δ_C (100.6 MHz, $CDCl_3$) 191.0, 164.9, 152.2, 133.8, 133.0, 131.7, 130.9, 130.8, 129.7, 128.7, 128.4, 121.9, 101.8, 78.2, 72.9, 29.0; HRMS (ESI): $[M^+ + Na]$, found 341.1156. $C_{21}H_{18}NaO_3$ requires 341.1154.

4.5.2. (E)-1-(3-Formyl-4-phenylbut-3-en-1-ynyl)cyclohexyl benzoate ***22***. Yield 0.570 g (82%); Gummy liquid; R_f (10% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3057, 2937, 2860, 2350 (w), 1721, 1688, 1600, 1452, 1310, 1277, 1249, 1107, 1019, 712; δ_H (400 MHz, $CDCl_3$) 9.58 (1H, s), 8.15–8.09 and 7.60–7.35 (11H, m), 2.40–1.79 and 1.69–1.43 (10H, m); δ_C (100.6 MHz, $CDCl_3$) 191.0, 164.7, 155.7, 155.6, 133.9, 133.0, 131.7, 131.0, 129.7, 128.7, 128.4, 122.2, 101.4, 80.3, 76.4, 25.3, 22.7; HRMS (ESI): $[M^+ + Na]$, found 381.1465. $C_{24}H_{22}NaO_3$ requires 381.1467.

4.5.3. (E)-1-(3-Formyl-4-phenylbut-3-en-1-ynyl)cyclopentyl benzoate ***23***. Yield 0.610 g (91%); White solid; Mp 76–78 °C; R_f (10% EtOAc/hexane) 0.35; IR (KBr, cm^{-1}) 3074, 2964, 2849, 1715, 1682, 1589, 1447, 1282, 1235, 1107, 761; δ_H (400 MHz, $CDCl_3$) 9.55 (1H, s), 7.59–7.33 and 8.12–8.08 (11H, m), 2.57–2.41 and 1.90–1.86 (8H, m); δ_C (100.6 MHz, $CDCl_3$) 190.9, 165.1, 151.9, 133.8, 133.0, 131.6, 130.8, 130.6, 129.6, 128.6, 128.4, 122.0, 101.5, 81.4, 78.8, 40.5, 23.5; HRMS (ESI): $[M^+ + Na]$, found 367.1310. $C_{23}H_{20}NaO_3$ requires 367.1310.

4.6. Synthesis of (*E*)-1-(3-benzylidene-4-hydroxypent-1-ynyl) cyclohexyl benzoate 24

A literature procedure[25] was modified. To a stirred solution of (*E*)-1-(3-formyl-4phenylbut-3-en-1ynyl)cyclohexyl benzoate **22** (400 mg, 1.1 mmol) in THF (8 mL) was added 1.6 M CH_3Li (0.75 mL, 1.0 mol equiv) slowly at −78 °C. The reaction mixture was allowed to reach rt while stirring and then quenched with saturated NH_4Cl solution (10 mL). Et_2O (20 mL) was added and the organic layer was washed with brine solution (20 mL), dried over anhyd Na_2SO_4 and concentrated. Compound **24** was separated from the crude by column chromatography using silica gel with ethyl acetate/hexane mixture as the eluent. Yield 0.194 g (46%, gummy liquid); [Found: C, 79.86; H, 7.45. $C_{25}H_{28}O_3$ requires C, 79.75; H, 7.50%]; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3470, 3061, 3027, 2936, 2861, 2350 (w), 2210 (vw), 1723, 1601, 1451, 1316, 1283, 1250, 1107, 1071, 1024, 918, 754, 712; δ_H (400 MHz, $CDCl_3$) 8.07–7.25 (10H, m), 6.71 (1H, s), 4.42 (1H, qrt, *J*=6.2 Hz), 2.37–2.05 (4H, m), 1.78–1.40 (6H, m), 1.28 (3H, d, *J*=7.2 Hz); δ_C (100.6 MHz, $CDCl_3$) 165.1, 135.9, 133.0, 132.8, 131.0, 129.7, 128.8, 128.3, 128.2, 126.0, 98.2, 83.5, 76.6, 72.4, 37.1, 25.2, 23.1, 22.7; LC/MS *m*/*z* 377 $[M+1]^+$.

4.7. General procedure for the synthesis of pyrans derivatives 25–42

To a solution of one of the hydroxyl propargylic esters [**4–20** or **24**; 0.5 mmol] in dry dichloromethane (DCM; 1 mL) was added a solution of Ph_3PAuCl (0.02 equiv) and $AgSbF_6$ (0.02 equiv) in DCM (1 mL). The contents were stirred at room temperature (25 °C) till the starting material was consumed. The solvent was removed under vacuum and crude product was purified by column chromatography using silica gel with ethyl acetate/hexane mixture as eluent to afford the corresponding product among **25–42**.

4.7.1. 5,6,7,8-Tetrahydro-2H-chromen-4-yl benzoate ***25***. Yield 0.096 g (75%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 2930, 2857, 1721, 1603, 1524, 1375, 1177, 1098, 1026, 941, 666; δ_H (400 MHz, $CDCl_3$) 8.08–7.41 (5H, m), 6.29 (1H, s), 5.25 (2H, s), 2.62–2.40 and 1.87–1.71 (8H, m); δ_C (100.6 MHz, $CDCl_3$) 166.5, 152.0, 147.0, 133.1, 129.9, 128.4, 118.0, 112.1, 59.1, 23.3, 23.1, 23.0, 22.1; HRMS (ESI): $[M^+ + Na]$, found 279.0998. $C_{16}H_{16}NaO_3$ requires *m*/*z* 279.0997.

4.7.2. 2,2-Dimethyl-6,7,8,8a-tetrahydro-2H-chromen-4-yl benzoate ***26***. Yield 0.102 g (72%); Gummy liquid; [Found: C, 76.12; H, 7.15. $C_{18}H_{20}O_3$ requires C, 76.03; H, 7.09%]; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3065, 2976, 2938, 2868, 1738, 1601, 1453, 1381, 1316, 1265, 1208, 1177, 1109, 1090, 1069, 1026, 710; δ_H (400 MHz, $CDCl_3$) 8.14–7.47 (5H, m), 5.73 (1H, br s), 5.54 (1H, s), 4.48 (1H, br s), 2.14–1.60 (6H, m), 1.44 and 1.40 (6H, two s); δ_C (100.6 MHz, $CDCl_3$) 164.7, 142.0, 133.5, 130.0, 128.6, 122.8, 121.4, 72.7, 67.7, 30.1, 29.3, 25.5, 25.3, 20.7; LC/MS *m*/*z* 285 $[M+1]^+$.

4.7.3. 6,7,8,8a-Tetrahydrospiro[chromene-2,1′-cyclohexane]-4-yl benzoate ***27***. Yield 0.105 g (65%); White solid; Mp 54–56 °C; R_f (1% EtOAc/hexane) 0.30; IR (KBr, cm^{-1}) 3063, 2932, 2859, 1738, 1665, 1632, 1601, 1451, 1391, 1264, 1171, 1088, 914, 708; δ_H (400 MHz, $CDCl_3$) 8.15–8.12 and 7.63–7.47 (5H, m), 5.70 (s), 5.62 (1H, s), 4.46 (1H, br s), 2.13–1.47 (16H, m); δ_C (100.6 MHz, $CDCl_3$) 164.6, 142.4, 133.5, 130.2, 130.0, 129.5, 128.6, 128.3, 122.1, 121.0, 73.5, 66.9, 38.4, 33.5, 29.3, 25.6, 25.3, 21.9, 21.7, 20.7; HRMS (ESI): $[M^+ + H]$, found 325.1803. $C_{21}H_{25}O_3$ requires 325.1803. X-ray structure was determined for this compound.

4.7.4. 6,7,8,8a-Tetrahydrospiro[chromene-2,1′-cyclopentane]-4-yl benzoate ***28***. Yield 0.122 g (78%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3047, 2951, 2855, 1732, 1663, 1594, 1444, 1263, 1168, 1066, 1029, 811, 710; δ_H (400 MHz, $CDCl_3$) 8.14–8.12 and 7.63–7.47 (5H, m), 5.72 (1H, br s), 5.55 (1H, s), 4.35 (1H, br s), 2.13–2.04 and 1.94–1.58 (14H, m); δ_C (100.6 MHz, $CDCl_3$) 164.7, 142.1, 133.5, 130.1, 129.9, 129.5, 128.6, 121.9, 121.2, 83.5, 68.5, 40.8, 36.4, 29.3, 25.3, 24.3, 24.1, 20.7; HRMS (ESI): $[M^+ + Na]$, found 333.1468. $C_{20}H_{22}NaO_3$ requires 333.1467.

4.7.5. 2-Ethyl-2-methyl-6,7,8,8a-tetrahydro-2H-chromen-4-yl benzoate ***29*** *(two diastereomers).* Yield 0.119 g (80%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3063, 2970, 2939, 2867, 1739, 1599, 1449, 1257, 1087, 1020, 709; δ_H (400 MHz, $CDCl_3$) 8.15–7.46 (10H, m), 5.72 and 5.71 (2H, two br s), 5.58 and 5.46 (2H, two s), 4.48 and 4.43 (2H, two br s), 2.12–1.83 and 1.71–1.58 (16H, m), 1.39 and 1.32 (6H, two s), 0.97 and 0.96 (6H, two t, *J*=7.4 and 7.6 Hz, respectively) [two diastereomers were there and hence the proton numbers are doubled in the assignment given here]; δ_C (100.6 MHz, $CDCl_3$) 164.7, 164.6, 142.7, 141.9, 133.5, 130.0, 129.9,

129.6, 129.5, 128.6, 122.7, 121.6, 121.2, 121.0, 75.1, 74.8, 67.5, 67.3, 35.5, 30.5, 29.2$_4$, 29.2$_0$, 25.9, 25.2, 24.2, 20.6$_4$, 20.6$_1$, 8.1; HRMS (ESI): [M$^+$+Na], found 321.1466. $C_{19}H_{22}NaO_3$ requires 321.1467.

4.7.6. 2,2-Dimethyl-6,7,8,8a-tetrahydro-2H-chromen-4-yl acetate ***30***. Yield 0.083 g (75%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 2976, 2940, 2870, 1759, 1680, 1634, 1435, 1372, 1198, 1144, 1084, 1040, 941, 901; δ_H (400 MHz, $CDCl_3$) 5.65 (1H, t, J=3.6 Hz), 5.40 (1H, s), 4.39 (1H, br s), 2.19 (3H, s), 2.16–1.58 (6H, m), 1.38 and 1.34 (6H, two s); δ_C (100.6 MHz, $CDCl_3$) 168.8, 141.9, 129.7, 122.6, 121.1, 72.5, 67.6, 30.1, 29.2, 25.5, 25.3, 20.8, 20.7; HRMS (ESI): [M$^+$+H], found 223.1334. $C_{13}H_{19}O_3$ requires 223.1336.

4.7.7. 6,7,8,8a-Tetrahydrospiro[chromene-2,1′-cyclohexane]-4-yl acetate ***31***. Yield 0.102 g (78%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 2936, 2861, 1761, 1676, 1624, 1451, 1370, 1206, 1171, 1082, 737; δ_H (400 MHz, $CDCl_3$) 5.63 (1H, br s), 5.48 (1H, s), 4.38 (1H, br s), 2.19 (3H, s), 2.15–2.14, 1.66–1.58 and 1.54–1.45 (16H, m); δ_C (100.6 MHz, $CDCl_3$) 168.9, 142.3, 130.2, 122.0, 120.8, 73.4, 66.8, 38.4, 33.5, 29.3, 25.6, 25.3, 21.9, 21.7, 20.9, 20.7; HRMS (ESI): [M$^+$+Na], found 285.1465. $C_{16}H_{22}NaO_3$ requires 285.1467.

4.7.8. 2,2-Dimethyl-6,7,8,8a-tetrahydro-2H-chromen-4-yl propionate ***32***. Yield 0.086 g (73%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 2978, 2940, 2868, 1763, 1667, 1632, 1462, 1358, 1177, 1144, 1080; δ_H (400 MHz, $CDCl_3$) 5.64 (1H, br s), 5.40 (1H, s), 4.40 (1H, br s), 2.50 (2H, qrt, J=7.6 Hz), 2.16–1.86 and 1.60–1.58 (6H, m), 1.39 and 1.34 (6H, two s), 1.22 (3H, t, J=7.6 Hz); δ_C (100.6 MHz, $CDCl_3$) 172.4, 141.7, 129.8, 122.5, 121.0, 72.5, 67.6, 30.1, 29.2, 27.5, 25.5, 25.3, 20.7, 9.2; HRMS (ESI): [M$^+$+Na], found 259.1312. $C_{14}H_{20}NaO_3$ requires 259.1310.

4.7.9. 2-Isobutyl-2-methyl-6,7,8,8a-tetrahydro-2H-chromen-4-yl benzoate ***33*** *(two diastereomers).* Yield 0.127 g (78%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3063, 3036, 2943, 2860, 1743, 1660, 1633, 1600, 1458, 1386, 1370, 1255, 1178, 1030, 915, 712; δ_H (400 MHz, $CDCl_3$) 8.15–8.13 and 7.63–7.47 (10H, m), 5.71 (2H, s), 5.52 and 5.49 (2H, two s), 4.46 (2H, br s), 2.13–2.05, 1.91–1.80 and 1.69–1.45 (18H, m), 1.39 and 1.37 (6H, two s), 1.05–0.89 (12H, m) [two diastereomers were there and hence the proton numbers are doubled in the assignment given here]; δ_C (100.6 MHz, $CDCl_3$) 164.7, 142.3, 141.9, 133.5, 130.1, 129.8$_2$, 129.8$_0$, 129.6, 128.6, 123.4, 122.2, 121.0, 75.4, 75.2, 67.5, 67.3, 51.2, 45.6, 29.4, 29.1, 27.0, 25.5, 25.3, 25.2, 24.8, 24.5, 24.4, 24.3, 23.8, 20.7; HRMS (ESI): [M$^+$+Na], found 349.1778. $C_{21}H_{26}NaO_3$ requires 349.1780.

4.7.10. 2-Methyl-2-pentyl-6,7,8,8a-tetrahydro-2H-chromen-4-yl benzoate ***34*** *(two diastereomers).* Yield 0.128 g (82%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 2959, 2931, 2871, 1737, 1600, 1452, 1375, 1260, 1085, 1063, 1025, 701; δ_H (400 MHz, $CDCl_3$) 8.15–7.48 (10H, m), 5.72 (2H, br s), 5.57 and 5.48 (2H, two s), 4.48 (2H, br s), 2.18–2.07 and 1.87–1.26 (34H, m), 0.90 and 0.89 (6H, two t, J=7.8 and 7.6 Hz, respectively) [two diastereomers were there and hence the proton numbers are doubled in the assignment given here]; δ_C (100.6 MHz, $CDCl_3$) 164.7, 142.5, 141.9, 133.6, 130.1, 129.9, 129.7, 129.6, 128.6, 122.9, 122.0, 121.3, 121.1, 75.0, 74.8, 67.5, 67.4, 43.0, 37.9, 32.3, 29.3, 26.7, 25.3, 24.6, 23.5, 23.4, 22.7, 20.7, 14.3, 14.1; HRMS (ESI): [M$^+$+Na], found 363.1938. $C_{22}H_{28}NaO_3$ requires 363.1936.

4.7.11. 2,2-Dipropyl-6,7,8,8a-tetrahydro-2H-chromen-4-yl benzoate ***35***. Yield 0.138 g (81%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 2959, 2940, 2866, 1737, 1458, 1277, 1173, 1085, 1025, 701; δ_H (400 MHz, $CDCl_3$) 8.15–7.47 (5H, m), 5.69 (1H, br s), 5.50 (1H, s), 4.46 (1H, br s), 2.12–2.04 and 1.87–1.32 (14H, m), 0.96–0.87 (6H, m); δ_C (100.6 MHz, $CDCl_3$) 164.8, 142.4, 133.5, 130.1, 129.9, 129.5, 128.6, 121.8, 120.9, 77.1, 67.4, 41.5, 39.9, 29.3, 25.3, 20.7, 17.1, 16.9, 14.8, 14.6; HRMS (ESI): [M$^+$+Na], found 363.1933. $C_{22}H_{28}NaO_3$ requires 363.1936.

4.7.12. 5-Benzyl-2H-Pyran-4-yl benzoate ***36***. Yield 0.094 g (64%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3063, 3030, 2926, 1769, 1725, 1603, 1584, 1495, 1453, 1269, 1109, 1026, 938, 708; δ_H (400 MHz, $CDCl_3$) 8.07–7.22 (11H, m), 6.35 (1H, s), 5.25 (2H, s), 3.76 (2H, s); δ_C (100.6 MHz, $CDCl_3$) 166.3, 150.0, 140.3, 133.2, 129.9, 128.4, 126.4, 125.5, 112.4, 58.8, 31.3; HRMS (ESI): [M$^+$+H], found 293.1177. $C_{19}H_{17}O_3$ requires 293.1179.

4.7.13. (Z)-3-Benzylidene-6,6-dimethyl-3,6-dihydro-2H-pyran-4-yl benzoate ***37***. Yield 0.144 g (90%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3059, 2976, 2932, 2851, 1738, 1601, 1493, 1453, 1265, 1206, 1177, 1150, 1109, 1059, 1024, 704; δ_H (400 MHz, $CDCl_3$) 7.49–6.80 (10H, m), 6.41 (1H, s), 5.61 (1H, s), 4.48 (2H, d, J=0.8 Hz), 1.46 (6H, s); δ_C (100.6 MHz, $CDCl_3$) 164.2, 142.0, 136.5, 132.9, 129.7, 128.8, 128.6, 127.7$_4$, 127.7$_0$, 127.5, 126.8, 126.7, 125.8, 74.0, 66.7, 27.4; HRMS (ESI): [M$^+$+Na], found 343.1310. $C_{21}H_{20}NaO_3$ requires 343.1310.

4.7.14. (Z)-3-Benzylidene-1-oxaspiro[5.5]undec-4-en-4-yl benzoate ***38***. Yield 0.148 g (82%); Gummy liquid; [Found: C, 79.85; H, 6.76. $C_{24}H_{24}O_3$ requires C, 79.97; H, 6.71%]; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3059, 3027, 2932, 2857, 2245, 1960, 1738, 1601, 1493, 1449, 1262, 1186, 1069, 1024, 704; δ_H (400 MHz, $CDCl_3$) 7.50–6.79 (10H, m), 6.40 (1H, s), 5.66 (1H, s), 4.46 (2H, s), 1.93–1.69 and 1.62–1.33 (10H, m); δ_C (100.6 MHz, $CDCl_3$) 164.2, 142.3, 136.6, 132.9, 129.7, 128.9, 128.6, 127.9, 127.7$_3$, 127.7$_0$, 126.6, 126.4, 125.5, 74.8, 66.1, 35.5, 25.5, 21.7; LC/MS m/z 361 [M+1]$^+$.

4.7.15. (Z)-8-Benzylidene-6-oxaspiro[4.5]dec-9-en-9-yl benzoate ***39***. Yield 0.149 g (86%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3062, 3020, 2956, 2913, 2849, 1731, 1656, 1603, 1454, 1262, 1171, 1070, 804, 702; δ_H (400 MHz, $CDCl_3$) 7.50–6.79 (10H, m), 6.40 (1H, s), 5.60 (1H, ~s), 4.41 (2H, s), 2.06–2.01 (2H, m), 1.89 and 1.73 (6H, two br s); δ_C (100.6 MHz, $CDCl_3$) 164.2, 142.1, 136.6, 132.9, 129.7, 128.9, 128.6, 127.7, 127.6, 126.6, 125.7, 125.6, 84.9, 67.4, 38.4, 24.2; HRMS (ESI): [M$^+$+Na], found 371.1622. $C_{23}H_{24}NaO_3$ requires 371.1623.

4.7.16. (Z)-3-Benzylidene-6-ethyl-6-methyl-3,6-dihydro-2H-pyran-4-yl benzoate ***40***. Yield 0.107 g (64%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}): 2970, 2929, 2851, 1733, 1650, 1454, 1257, 1107, 1061, 1024; δ_H (400 MHz, $CDCl_3$) 7.49–6.83 (10H, m), 6.41 (1H, s), 5.57 (1H, s), 4.54 and 4.38 (2H, 2 d, J=12.4 Hz each), 1.78–1.73 (2H, m), 1.39 (3H, s), 1.03 (3H, t, J=7.6 Hz); δ_C (100.6 MHz, $CDCl_3$) 164.3, 142.6, 136.6, 132.9, 129.7, 128.9, 128.6, 127.8, 127.7, 126.7, 125.9, 125.6, 76.4, 66.6, 33.7, 24.4, 8.2; HRMS (ESI): [M$^+$+Na], found 357.1467. $C_{22}H_{22}NaO_3$ requires 357.1467.

4.7.17. (Z)-3-Benzylidene-6,6-dimethyl-3,6-dihydro-2H-pyran-4-yl acetate ***41***. Yield 0.096 g (74%); Gummy liquid; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}) 3058, 3027, 2979, 2934, 1761, 1620, 1449, 1370, 1198, 1149, 1054, 1019, 900, 739, 700; δ_H (400 MHz, $CDCl_3$) 7.30–7.22 (5H, m), 6.36 (1H, s), 5.45 (1H, s), 4.41 (2H, s), 1.40 (6H, s), 1.27 (3H, s); δ_C (100.6 MHz, $CDCl_3$) 168.5, 141.9, 136.6, 129.2, 127.7, 127.2, 127.0, 126.7, 125.2, 73.8, 66.6, 27.3, 19.5; HRMS (ESI): [M$^+$+Na], found 281.1155. $C_{16}H_{18}NaO_3$ requires 281.1154.

4.7.18. (Z)-3-Benzylidene-2-methyl-1-oxaspiro[5.5]undec-4-en-4-yl benzoate ***42***. Yield 0.161 g (86%); Gummy liquid; [Found: C, 80.25; H, 6.91. $C_{25}H_{26}O_3$ requires C, 80.18; H, 7.00%]; R_f (1% EtOAc/hexane) 0.30; IR (neat, cm^{-1}): 3061, 2930, 2855, 1736, 1601, 1451, 1262, 1179, 1088, 1024, 739, 704; δ_H (400 MHz, $CDCl_3$) 7.44–7.00 (10H, m), 6.46

(1H, s), 5.67 (1H, s), 4.61 (1H, qrt, J=6.0 Hz), 1.99–1.33 (10H, m), 1.53 (3H, br s); δ_C (100.6 MHz, $CDCl_3$) 164.4, 143.0, 137.4, 133.1, 132.8, 130.2, 129.7, 129.0, 128.8, 127.7, 126.7, 125.9, 123.4, 74.2, 67.7, 38.6, 33.6, 25.6, 22.1, 21.7, 18.4; LC/MS m/z 377 $[M+1]^+$.

4.8. Synthesis of phosphorus containing β-hydroxy propargyl esters 43–45

Compound **43**: This compound was synthesised by a literature procedure[18] by using **21** (0.300 g, 0.9 mmol), and *H*-phosphonate ($OCH_2CMe_2CH_2O$)P(O)H (0.131 g, 0.9 mmol). Yield 0.405 g (92%); Mp 148–150 °C; R_f (50% EtOAc/hexane) 0.40; IR (KBr, cm^{-1}) 3178, 2986, 2964, 2934, 2250 (vw), 1721, 1474, 1452, 1293, 1260, 1112, 1085, 833, 767, 712; δ_H (400 MHz, $CDCl_3$) 8.04–7.27 (10H, m), 6.93 (d, J=4.4 Hz), 4.79 (1H, dd, J=11.2 and 5.4 Hz), 4.44–4.33 (2H, m), 4.05–3.90 (3H, m), 1.89 (6H, s), 1.18 and 0.88 (6H, two s); δ_C (100.6 MHz, $CDCl_3$) 165.6, 137.8 (d, J=11.1 Hz), 135.3 (d, J=2.1 Hz), 133.3, 130.5, 129.7, 129.1, 128.9, 128.4, 128.2, 116.3, 99.5, 81.2 (d, J=4.2 Hz), 78.1$_4$, 78.1$_0$, 73.7 (d, J=159.0 Hz), 73.1, 32.5 (d, J=7.6 Hz), 28.7, 28.6, 22.0, 20.8; ^{31}P NMR (162 MHz, $CDCl_3$) 12.9; HRMS (ESI): $[M^+ + H]$, found 469.1781. $C_{26}H_{30}O_6P$ requires 491.1781.

Compound **44**: This compound was synthesised by using **22** (0.300 g, 0.8 mmol), and *H*-phosphonate ($OCH_2CMe_2CH_2O$)P(O)H (0.131 g, 0.9 mmol). Yield 0.387 g (91%); Mp 190–192 °C; R_f (50% EtOAc/hexane) 0.40; IR (neat, cm^{-1}) 3150, 2970, 2931, 2855, 2300 (vw), 1720, 1447, 1282, 1255, 1195, 1112, 1085, 1052, 1019, 833, 811, 762, 707; δ_H (400 MHz, $CDCl_3$) 8.05–7.29 (10H, m), 6.92 (1H, d, J=4.0 Hz), 4.78 (1H, d, J=10.8 Hz), 4.45–4.41 and 4.33–4.28 (2H, m), 4.05–3.89 (2H, m), 2.37–2.05 and 1.81–1.75 (10H, m), 1.18 and 0.87 (6H, two s); δ_C (100.6 MHz, $CDCl_3$) 165.6, 137.7, 137.6, 135.4, 133.3, 130.7, 129.7, 129.1, 128.8, 128.5, 128.2, 116.5, 98.9, 83.9 (d, J=3.4 Hz), 78.1 (dd→t, J=6.8 Hz each), 73.9 (d, J=157.9 Hz), 36.9, 36.8, 32.5 (d, J=7.2 Hz), 25.1, 22.6, 22.5, 22.0, 20.8; ^{31}P NMR (162 MHz, $CDCl_3$) 12.9; HRMS (ESI): $[M^+ + Na]$, found 531.1913. $C_{29}H_{33}NaO_6P$ requires 531.1913.

Compound **45**: This compound was synthesised by using **22** (0.300 g, 0.8 mmol), and phosphine oxide $Ph_2P(O)H$ (0.162 g, 0.8 mmol). Yield 0.400 g (85%); Gummy liquid; [Found: C, 77.32; H, 5.85. $C_{36}H_{33}O_4P$ requires C, 77.13; H, 5.93%]; R_f (50% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3448, 3059, 2935, 2858, 2200 (vw), 1719, 1600, 1437, 1282, 1245, 1107, 713; δ_H (400 MHz, $CDCl_3$) 8.02–7.28 (20H, m), 6.90 (1H, d, J=4.0 Hz), 5.19 (1H, d, J=6.0 Hz), 1.95–1.36 (10H, m); δ_C (100.6 MHz, $CDCl_3$) 165.0, 137.7, 137.6, 135.6, 133.1, 132.6, 132.5, 132.2, 132.1, 131.9, 131.5, 130.9, 129.7, 129.0, 128.6, 128.3$_2$, 128.3$_0$, 128.2, 128.1, 116.4, 99.1, 83.0, 75.9 (d, J=79.5 Hz), 74.7, 36.7, 36.5, 25.0, 22.4; ^{31}P NMR (162 MHz, $CDCl_3$) 28.9; LC/MS m/z 561 $[M+1]^+$.

4.9. General procedure for the synthesis of phosphono-/phosphinoyl-furans and pyran derivatives 46–48

To a solution of one of the hydroxy propargylic esters **43**–**45** (0.5 mmol) in dry DCM (1 mL) was added a solution of Ph_3PAuCl (0.03 mol equiv) and $AgSbF_6$ (0.03 mol equiv) in DCM (1.0 mL). The contents were stirred at 70 °C (oil bath temperature) till the starting material was consumed. The solvent was removed under vacuum and crude product was purified by column chromatography using silica gel with ethyl acetate/hexane (1:1) mixture as eluent to afford one of the products **46**–**48**.

Compound **46**. Yield 0.103 g (44%); Mp 134–138 °C; R_f (40% EtOAc/hexane) 0.25; IR (KBr, cm^{-1}) 3058, 2964, 2926, 2855, 1737, 1658, 1452, 1249, 1195, 1096, 1069, 1014, 811, 723; δ_H (400 MHz, $CDCl_3$) 8.12–6.88 (11H, m), 5.75 (1H, d, J=0.8 Hz), 5.19 (1H, dd, J=13.0 and 1.4 Hz), 4.60 (2H, dd, J=18.8 and 10.0 Hz), 4.09–3.94 (2H, m), 1.52 and 1.49 (6H, two s), 1.35 and 0.90 (6H, two s); δ_C (100.6 MHz, $CDCl_3$) 164.0, 142.2 (d, J=12.9 Hz), 136.7, 133.4, 133.0, 130.1, 129.6, 128.8, 128.7, 128.4, 127.7, 126.9, 125.6, 123.4, 79.9 and 79.0 (2 d, J=7.3 and 7.0 Hz, respectively), 75.2 (d, J=14.1 Hz), 73.1 (d, J=166.2 Hz), 32.5 (d, J=8.5 Hz), 29.5, 25.4, 22.4, 20.8; ^{31}P NMR (162 MHz, $CDCl_3$) δ 9.0; HRMS (ESI): $[M^+ + H]$, found 469.1782. $C_{26}H_{30}O_6P$ requires 469.1782.

Compound **47**. Yield 0.120 g (62%). The spectral data are in accordance with the literature report.[4e]

Compound **48**. Yield 0.062 g (28%); Mp 96–98 °C; R_f (40% EtOAc/hexane) 0.25; IR (KBr, cm^{-1}) 3063, 3030, 2932, 2858, 1666, 1600, 1436, 1266, 1162, 1123, 707; δ_H (400 MHz, $CDCl_3$) 8.10–7.47 and 7.25–7.16 (15H, m), 6.18 (1H, br s), 6.06 (1H, s), 4.12 (2H, s), 2.19–2.13 and 1.67–1.58 (8H, m); δ_C (100.6 MHz, $CDCl_3$) 159.9 (d, J=6.2 Hz), 140.2, 140.0 (d, J=6.3 Hz), 133.3, 132.8 (d, J=100.7 Hz), 131.8, 131.7, 130.1, 129.0, 128.6, 128.4, 126.9, 126.1, 125.7, 107.1 (d, J=8.9 Hz), 31.2, 25.3, 24.8, 22.2, 22.0; ^{31}P NMR (162 MHz, $CDCl_3$) δ 18.5; HRMS (ESI): $[M^+ + H]$, found 439.1828. $C_{29}H_{28}O_2P$ requires 439.1828.

4.10. Synthesis of β-hydroxy propargylic esters 49, 50

These compounds were synthesised by following a procedure similar to that for **15**–**20**.

*4.10.1. (E)-1-(3-(Hydroxymethyl)-4-phenylbut-3-en-1-ynyl)cyclohexyl acetate **49**.* This compound was synthesised from **2** (400 mg, 1.54 mmol) and **3g** (1.5 equiv). Yield 0.268 g (56%); Gummy liquid; [Found: C, 76.58; H, 7.36. $C_{19}H_{22}O_3$ requires C, 76.48; H, 7.43%]; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3461, 3060, 3025, 2938, 2861, 2310 (w), 2190 (vw), 1742, 1601, 1495, 1449, 1368, 1267, 1233, 1022, 963, 916, 756, 694; δ_H (400 MHz, $CDCl_3$) 7.84–6.71 (6H, m), 4.28 (2H, d, J=4.8 Hz), 2.60 (1H, br s), 2.24–2.21 (2H, m), 2.07 (3H, s), 1.90–1.57 (8H, m); δ_C (100.6 MHz, $CDCl_3$) 169.9, 135.9, 133.7, 128.7, 128.3, 128.2, 121.5, 97.8, 84.1, 76.1, 67.4, 37.0, 25.2, 22.7, 22.1; LC/MS m/z 299 $[M+1]^+$.

*4.10.2. (E)-5-(Hydroxymethyl)-2-methyl-6-phenylhex-5-en-3-yn-2-yl propionate **50**.* This compound was synthesised from **2** (400 mg, 1.54 mmol) and **3h** (1.5 equiv). Yield 0.327 g (78%); Gummy liquid; R_f (20% EtOAc/hexane) 0.35; IR (neat, cm^{-1}) 3459, 3059, 2986, 2940, 2867, 2350 (vw), 2210 (w), 1742, 1599, 1449, 1381, 1362, 1254, 1190, 1125, 1078, 918, 874, 808, 756, 694; δ_H (400 MHz, $CDCl_3$) 7.83–6.72 (6H, m), 4.27 (2H, s), 2.52 (1H, br s), 2.33 (3H, qrt, J=6.8 Hz), 1.74 (6H, s), 1.14 (3H, t, J=7.4 Hz); δ_C (100.6 MHz, $CDCl_3$) 173.3, 135.8, 133.8, 128.6, 128.2, 128.1, 121.1, 98.2, 82.1, 72.2, 66.9, 28.8, 28.3, 9.0; HRMS (ESI): $[M^+ + Na]$, found 295.1310. $C_{17}H_{20}NaO_3$ requires 295.1310.

4.11. Synthesis of macrocycles 51a,b and 52

These compounds were synthesised by following a procedure similar to that for **25**–**42** by using one of the hydroxy propargylic esters (**49**–**50**, 0.5 mmol).

Compound **51a**. Yield 0.033 g (28%); White solid; Mp 120–122 °C; [Found: C, 85.56; H, 7.71. $C_{34}H_{36}O_2$ requires C, 85.67; H, 7.61%]; R_f (1% EtOAc/hexane) 0.33; IR (KBr, cm^{-1}) 3058, 3025, 2934, 2857, 1721, 1599, 1449, 1339, 1289, 1260, 1144, 1084, 752, 693; δ_H (400 MHz, $CDCl_3$) 7.85–7.23 (10H, m), 6.88 (2H, s), 4.34 (4H, s), 2.06–1.55 and 1.35–1.29 (20H, m); δ_C (100.6 MHz, $CDCl_3$) 136.5, 132.9, 128.7, 128.1, 127.9, 119.6, 97.3, 84.6, 75.2, 66.9, 37.3, 25.6, 23.0; LC/MS m/z 475 $[M-1]^+$.

Compound **51b**. Yield 0.052 g (44%); White solid; Mp 178–180 °C; R_f (1% EtOAc/hexane) 0.30; IR (KBr, cm^{-1}) 2963, 2856, 1948, 1599, 1495, 1447, 1412, 1262, 1103, 866, 801, 693; δ_H (400 MHz, $CDCl_3$) 7.91–7.27 (10H, m), 6.71 (2H, s), 4.38 (4H, s), 2.12–1.63 (18H, m), 1.32 (2H, br s); δ_C (100.6 MHz, $CDCl_3$) 136.0, 128.8, 128.4, 128.1, 119.9, 98.9, 84.8, 76.8, 70.3, 37.5, 25.6, 23.3; HRMS (ESI): $[M^+ + H]$,

found 477.2793. $C_{34}H_{37}O_2$ requires 477.2795. X-ray structure has been determined for this compound.

Compound **52**. Yield 0.059 g (60%); Low melting solid; R_f (1% EtOAc/hexane) 0.30; IR (KBr, cm^{-1}) 2978, 2932, 2859, 2170, 2160, 1659, 1622, 1449, 1360, 1179, 1150, 1073, 739, 696; δ_H (400 MHz, $CDCl_3$) 7.84–7.29 (10H, m), 6.67 (2H, s), 4.37 (4H, s), 1.61 (12H, s); δ_C (100.6 MHz, $CDCl_3$) 136.0, 135.8, 128.6, 128.5, 128.2, 119.5, 99.6, 83.0, 72.7, 71.0, 28.9; HRMS (ESI): [M^++Na], found 419.1989. $C_{28}H_{28}NaO_2$ requires 419.1987.

Single crystal X-ray data for compounds **27** and **51b** were collected on a Bruker AXS-SMART or OXFORD diffractometer using Mo K_α (λ=0.71073 Å) radiation. The structures were solved by direct methods and refined by full-matrix least squares method using standard procedures.[26] Absorption corrections were done using SADABS program, where applicable. In general, all non-hydrogen atoms were refined anisotropically; hydrogen atoms were fixed by geometry or located by a Difference Fourier map and refined isotropically.

Compound **27**: colourless block, $C_{21}H_{24}O_3$, M=320.40, Orthorhombic, Space group $Pn2_{1a}$, a=10.0016(6), b=9.3235(8), c=18.6290(17) Å, V=1737.2(2) $Å^3$, Z=4, μ=0.082 mm^{-1}, data/restraints/parameters: 2763/1/217, Flack parameter −1.4(15), R indices ($I>2\sigma(I)$): $R1$=0.0557, $wR2$ (all data)=0.0934. The configuration at C1 as shown by checkcif is *R*. CCDC No. 924016.

Compound **51b**: colourless block, $C_{34}H_{36}O_2$, M=476.63, Monoclinic, Space group $C2/c$, a=28.650(4), b=9.830(1), c=22.383(2) Å, β=121.74(2), V=5361(1) $Å^3$, Z=8, μ=0.071 mm^{-1}, data/restraints/parameters: 4715/0/325, R indices ($I>2\sigma(I)$): $R1$=0.1562, $wR2$ (all data)=0.1180, CCDC No. 924018.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2013.07.003.

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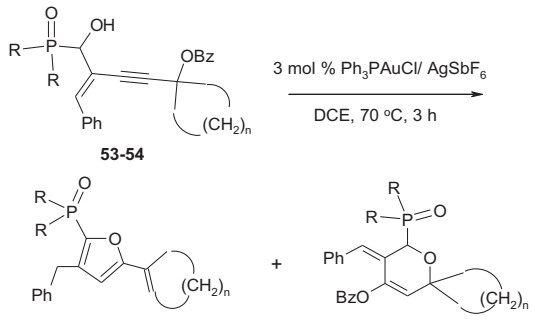
19. Phosphono-alkynols **53**, **54** led to phosphono-furans **55**, **56**, respectively, in addition to the corresponding phosphono-pyrans **55′**, **56′**. In these cases, two products, a *phosphonofuran* and a *phosphonopyran* with very close R_f values were formed in varying proportions [^{31}P NMR evidence], but the reaction was quantitative and the phosphono-alkynol completely consumed. We could isolate the phosphono-furans **55**, **56** (see Supplementary data; and CCDC 924017 for **56**) in a pure state.



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