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A relay ring-closing metathesis/Diels-Alder approach to sugar-derived pluramycin-hybrids†‡

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Herein, we present a general approach for synthesizing pluramycin hybrids, which are analogous to the pluramycinone carbocyclic skeleton. This method involves a sequence of relay ring-closing enyne metathesis, Diels–Alder and oxidative aromatization reactions to synthesize pluramycinone-sugar hybrids. As part of our ongoing research, we have successfully synthesized two pluramycin hybrid analogues by carefully monitoring the late-stage oxidative aromatization steps, which depend on the stereo-orientation of the Diels–Alder cycloadduct at the C-4 center. The undesired ring-opening product can also serve as a *C*-glycoside analog, providing a versatile convergent route to access both types of hybrids and highlighting the significance of this strategy.

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Introduction

Natural products have historically provided crucial insights into biological processes due to their intricate chemical makeup and have been comprehensively investigated in relation to their biosynthesis and mechanisms of action. It is worth noting that numerous natural products have proven to be valuable substances or starting compounds in various industries, including fragrances, crop science, and pharmaceuticals.

In fact, over 40% of recently approved drugs are either natural products or derived from them.¹ However, many traditional drugs have become ineffective due to multidrug resistance (MDR), posing a significant challenge in the field. To overcome this obstacle, scientists have made significant progress in identifying new synthetic compounds with enhanced therapeutic properties. Among the various strategies for rapidly synthesizing a diverse range of molecules, the hybrid approach has emerged as one of the methods, as it combines structural features from different classes of compounds to produce distinct compounds with modified or unprecedented biological activities in a short time frame.^{2,3} The drive for the creation of these hybrids has been derived from nature, which employs mixed biosynthesis pathways to produce various bioactive natural products (Fig. 1),4-6 for example, an intricate indole alkaloid, such as strychnine (1), which is derived from the amino acid tryptophan and the monoterpenic precursor

loganin,^{5*a,b*} and ansa antibiotics, such as rifamycins (3)^{5*c,d*} in which the aromatic core is derived from shikimate and the ansa chain from polyketides. On the other hand, glycoproteins, chlorophyll-a (2), vitamin E (4), and vinblastine (5) (Fig. 1) are notable examples of naturally occurring hybrid molecules, where different segments of the molecule have diverse biosynthetic origins but are firmly bonded together to form a functional unit.^{5,6} Drawing on this natural process, synthetic chemists have designed and synthesized several hybrid compounds comprising both natural and unnatural elements with various biological functions. These hybrid molecules, existing as dimers or polymers, may exhibit a behaviour that is distinct from those of their monomeric counterparts.



Fig. 1 Representative examples of hybrid natural products derived from biosynthetic pathways.

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Anthrapyran antibiotics constitute a diverse range of natural products obtained from various terrestrial and marine *Streptomyces* sp. strains as secondary metabolites. These compounds feature a distinct 4H-anthra[1,2-*b*]-pyran-4,7,12-trione nucleus (Fig. 2) and exhibit versatile and potent biological activities, making them appealing synthetic targets (**6–10**).^{7*a*,*c*-*e*} Apart from their significant biological activity profile, it has been found that these families of natural products display prominent chemical instability. They are sensitive to heat and decompose when exposed to temperatures exceeding 60 °C.^{7*b*}

In addition, a considerable portion of these compounds was discovered to be unstable when exposed to ultraviolet light or sunlight.^{7b,c} They also exhibit high cytotoxicity and low solubility issues. Due to these factors, they have not been investigated much in clinical trials despite exhibiting widespread biological activities, including antitumor properties. Given our laboratory's interest in the total synthesis of biologically active natural products and their analogues, we have designed and synthesised several interesting classes of hybrid molecules derived from sugar as the chiral backbone.⁸ In this work, we report a general approach by exploring the RRCEM (relay ring-closing enyne metathesis) as a key step to access the pluramy-cinone family of natural product analogues.

Results and discussion

The synthesis of hybrid natural products using chemical methods offers a means for rapidly accessing diverse structural compounds ready for pharmacological testing. Our strategy includes a sequential relay ring-closing enyne metathesis/ Diels–Alder approach to synthesize the required tetracyclic core skeleton 3,4-dihydro-2*H*-anthra[1,2-*b*]-pyran-7,12-dione, as depicted in Scheme 1.

Retrosynthetic analysis of diene 11

We anticipated that the chiral diene **11** could be accessed by a relay ring-closing enyne metathesis (RRCEM) from the enyne





precursor **12**, which, in turn, could be accessed in three steps from alkyne **13** *via* a diastereoselective oxa-Michael addition with ethyl propiolate and the reduction of the resultant ester to primary alcohol followed by *O*-allylation reaction. Alcohol **13** could be synthesized in two steps from alkynol **14** *via* protection of alkynol and removal of the PMB group. The alkyne functionality on alcohol **14** could be installed by diastereoselective nucleophilic addition of the terminal alkyne into the known aldehyde **15**, which in turn could be prepared from commercially available D-glucose in four steps (Scheme 2) by following known literature procedure (see the ESI[‡]).⁹

Our synthesis began with the incorporation of the alkyne functionality into the known aldehyde **15** through a diastereoselective nucleophilic addition reaction. The addition of the lithium anion of TMS acetylene **16** with *n*-BuLi resulted in only 24% yield of the addition product **17** (Scheme 3). However, when TBDPS-protected propargylic alcohol **18** was employed



Fig. 2 Selected examples of pluramycin/pluramycinone natural products.



Scheme 2 Retrosynthetic analysis for diene 11.



under the same conditions, alcohol **14** was obtained in 46% yield as a single isomer. Attempts to use an *in situ* generated organocerium reagent (prepared from anhydrous cerium chloride and *n*-BuLi) did not improve the yield and diastereo-selectivity of the product. So, we decided to move further with alcohol **14** obtained in a moderate yield. Attempts to protect the alcohol as MOM ether under different conditions did not give a good yield of the expected product. Thus, efforts were redirected towards using a less sterically hindered ether-protecting group, such as benzyl, which was smoothly incorporated by using benzyl bromide with NaH in DMF to provide the desired benzyl ether product **20** (Scheme 4).

The next objective was to selectively remove the PMB group of **20**, which was easily achieved by treating with DDQ to provide alcohol **13** in 70% yield. The oxa-Michael addition reaction of **13** with ethyl propiolate in the presence of *N*-methylmorpholine (NMM) delivered ester **21**, which was immediately reduced with DIBAL-H to furnish the allylic alcohol **22** in 85% yield (Scheme 5).

When 22 was subjected to *O*-allylation by treating it with NaH and allyl bromide, the key enyne precursor 12 was obtained only in 40% yield. It was observed that a minor undesired double *O*-allylated product, 23, was formed during this reaction. This unwanted by-product resulted from the deprotection of the TBDPS group under basic conditions followed by a second allylation (Scheme 5). After multiple



Scheme 5 Synthesis of the enyne precursor 12.

attempts to prevent the formation of the unwanted product **23** using various bases, including NaH, potassium *tert*-butoxide and solvents such as DMF and THF, we were unsuccessful in controlling the formation of **23**. The low yield and decomposition of the starting materials appeared to have forced us to abandon this route.

At this stage, it became evident that a stable protecting group was crucial to overcome this problem to obtain a substantial quantity of the enyne precursor product. Consequently, we chose to replace the TBDPS protecting group with the robust benzyl group. Subsequently, we performed nucleophilic addition of the benzyl-protected propargylic alcohol 24 to aldehyde 15, which resulted in the formation of a mixture of diastereomers 25 and 26 (dr = 1:2), with a combined yield of 80% (Scheme 6). The conversion of the minor isomer 25 into the major isomer 26 was achieved exclusively through sequence of oxidation and reduction reactions. Initially, the minor diastereomer was oxidized using DMP oxidation, which resulted in the formation of an alkynone product, which was subsequently reduced using various redu-



Scheme 4 Synthesis of compounds 19 and 20

 $\begin{array}{c} \begin{array}{c} & & & \\ OBn & 24 \\ PMBO & & \\ 15 \end{array} \end{array} \xrightarrow{PBuLi, THF} \\ \hline PMBO & \\ 15 \end{array} \xrightarrow{PBO}_{dr = 1:2, 80\%} \\ \begin{array}{c} & & \\ OBn \\ & \\ 25 \end{array} \xrightarrow{OBn}_{25} \\ \hline \\ & \\ OBn \\ OB$

Scheme 6 Synthesis of alcohols 25 and 26.

cing reagents with the aim of obtaining a single isomer of alcohol 26 (see the ESI[‡]) (Scheme 6). Among the various options, diisobutylaluminium hydride (DIBAL-H), a sterically hindered electrophilic hydride donor, was found to be much more efficient and predominantly produced a single isomer of alcohol 26. The major isomer of 26 was then protected as benzyl ether 27 in 72% yield. Now, the chemo-selective removal of the PMB group with DDQ proceeded smoothly to afford alcohol 28 in 80% yield. The oxa-Michael addition of alcohol 28 with ethyl propiolate in the presence of N-methylmorpholine furnished the conjugate ester 29 in 68% vield. Reduction of 29 with DIBAL-H afforded the allylic alcohol 30, which, upon O-allylation using NaH and allyl bromide, afforded the O-alkylated product 31 in good yield via two steps. Having sufficient quantity of the envne precursor 31 in hand, we proceeded to carry out the first key step (relay ringclosing enyne metathesis) with the Grubbs' second-generation catalyst (G-II). To our delight, this reaction worked well to afford the desired diene product 32 in 80% yield within 30 min (Scheme 7).

With diene 32 in hand, we next focused our efforts on the sequential Diels–Alder-aromatization reaction by exposing it to various quinone dienophiles to obtain the tetracyclic framework of pluramycin hybrids. Initially, diene 32 was heated in toluene at 100 to 110 °C with commercially available 1,4-naphthoquinone 33, which resulted in a crude cycloadduct 34 in 24 h. However, when this crude product was subjected to aromatization under air and the SiO₂-Et₃N reagent mixture, contrary to our expected tetracycle 35, we observed the formation of the ring-cleaved aromatized product 36 (Scheme 8). The plausible mechanism for ring opening product is shown in Scheme 9.



Scheme 7 Synthesis of diene 32.



Scheme 8 Attempted conditions for tetracycle 35.



Scheme 9 Plausible reaction mechanism for the aromatization of cycloadduct 34.

The formation of Cycloadduct intermediate **34** was confirmed by high resolution mass spectrometry (HRMS) data (see the ESI‡) and at this stage we realized that the Diels–Alder reaction proceeded smoothly, but further optimization is required for the aromatization step.

The use of milder bases, such as Et_3N (entry 1) and K_2CO_3 (entry 2), did not yield the desired aromatic tetracyclic product **35**; instead, it provided the ring-cleaved product **36** exclusively. At this point, it became apparent that basic conditions may not be suitable for obtaining the desired product, as C–O bond cleavage is more facile under basic conditions due to its better-leaving group capability. As a result, 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ)¹⁰ was used to provide the expected tetracyle, but this reagent also unfortunately provided a complex mixture (entry 3, Table 1). Since direct aromatization of cycloadduct **34** was unsuccessful under various conditions, we anticipated that prior functionalization of the cyclohexene intermediate **34**, before aromatization, might

Table 1 Attempted conditions for aromatization



Entry	Reaction conditions	Time	Result
1	Et ₃ N, SiO ₂ , CHCl ₃	1 h	36 $(56\%)^a$
2	K ₂ CO ₃ , MeOH	2 h	36 $(50\%)^a$
3	DDQ, CH_2Cl_2	12 h	Complex mixtur
4	NBS, THF : $H_2O(5:1)$ then Et_3N , CH_2Cl_2	8 h	Complex mixture
5	OsO_4 , NMO, acetone : $H_2O(5:1)$	24 h	36 $(45\%)^a$
6	<i>m</i> -CPBA, NaHCO ₃ , CH_2Cl_2	24 h	NR ^b

 a Isolated overall yield. NR = no reaction. b Only the starting material remains.

facilitate the process to provide the desired product **35**. Thus, attempts were made to form the bromohydrin intermediate *via* a bromonium ion (entry 4, Table 1), but this reaction also led to a complex mixture. Inspired by the seminal work done by Krohn and co-workers,^{11*a*} we subjected the crude cycloadduct **34** to hydroxylation by exposing it to a catalytic amount of osmium tetroxide along with the co-oxidant *N*-methylmorpholine-*N*-oxide (NMO) (entry 5, Table 1).

The NMR analysis of the crude mixture revealed that a product with ring cleavage and aromatization was formed during the hydroxylation step. We presumed that the in situ generation of N-methylmorpholine would have facilitated the elimination process by means of a base-induced elimination process. Recently, Collet and co-workers reported a strategy wherein the Diels-Alder cycloadduct intermediate was subjected to a one-pot epoxidation followed by aromatization to furnish the aromatic tetracyclic natural product.^{11b} However, our attempts to use similar conditions to synthesize the anthrapyran analogue from the cyclohexene intermediate 34 with m-CPBA in dichloromethane (entry 6) were unsuccessful.¹² Further, when we carried out the Diels-Alder reaction of 32 with a known and activated brominated dienophile 37, the required crude cycloadduct intermediate was obtained in 15 h. However, the addition of a triethyl amine base resulted in the immediate formation of the C-O bond cleavage product 39 in 50% yield over two steps (Scheme 10). Efforts to epoxidize the cyclohexene adducts 38 were unsuccessful despite repeated attempts. Furthermore, our efforts to isolate the cyclohexene intermediate 38 using silica gel or neutral alumina column chromatography were unsuccessful, as it is seems to be unstable during purification and hence immediately subjected to aromatization conditions after the consumption of diene 32 (Scheme 10).

We presumed that the presence of two bulky benzyloxy groups around the cyclohexene double bond of **38** might be



Scheme 10 Attempted aromatization conditions with tetracycle 38.

blocking the epoxidation from both faces of the alkene. As a result, we redirected our attention towards synthesizing an epimer of diene **32** to address this issue.

Following a similar reaction sequence, diene **41** was successfully synthesized from alcohol **25** in 6 steps in an overall yield of 32% (Scheme 11). At this stage, the stereochemical orientation of the newly formed stereocenter in the synthesis of **25** and **26** (Scheme 6) was confirmed by NOE NMR analysis of **41** (see the ESI‡), which also resolves the relative configuration of the key intermediate **32** and all compounds derived further.

Synthesis of hybrid 42

When the minor diastereomer of diene, *i.e.* **41**, was subjected to Diels–Alder reaction conditions with the commercially available 1,4-naphthaquinone **33**, the crude cycloadduct product was delivered within 24 h. The crude cyclohexene adduct was then directly used for epoxidation with *m*-CPBA in DCM. After 12 h, to our delight, TLC showed complete consumption of the starting materials, and we were pleased to observe the formation of the epoxide product. After consumption of the starting material, the crude epoxide was then directly treated with excess triethylamine in the same pot under an open-air atmosphere, resulting in the desired tetracyclic analogue **42** in an overall yield of 45% over three steps (Scheme 12).



Scheme 11 Synthesis of the minor diene isomer 41 from alcohol 25.



Scheme 12 Synthesis of the pluramycin-sugar hybrid 42.

The plausible reaction mechanism for the aromatization *via* epoxide ring opening reaction is depicted in Scheme 13.

Synthesis of hybrid 45

Given the biological importance of juglone **43** and the presence of hydroxyl groups in numerous natural products from the pluramycin family, we were motivated to create a sugar hybrid analog of juglone. To achieve this aim, juglone **43** was subjected to optimized Diels–Alder reaction conditions with diene **41** in toluene at 100 to 110 °C, resulting in the formation of the cycloadduct intermediate **44** within 20 h. The crude cycloadduct mixture was dried under vacuum and re-dissolved in dichloromethane and then treated with *m*-CPBA, and it led to the formation of a crude epoxide mixture. This mixture was then immediately subjected to aromatization within the same pot by adding an excess of Et₃N to the reaction mixture in an open-air atmosphere, resulting in the desired pluramycin-sugar hybrid **45** in 50% overall yield over three steps (Scheme 14).

However, when the same sequence was attempted with the major diene 32, the C–O bond cleaved product 46 was obtained in 40% yield over three steps (Scheme 15).



Scheme 13 Plausible reaction mechanism for the aromatization step.



Scheme 14 Synthesis of the pluramycin-sugar hybrid 45.



Scheme 15 Synthesis of the sugar-quinone hybrid 46.

In this study, our attempts to isolate any of the cycloadducts seem challenging, as they either lead to the ring-opening product or the decomposition of the product. Therefore, we decided to subject them immediately to subsequent steps after their formation.

Conclusions

In conclusion, we have developed a simple convergent strategy for the synthesis of a new class of sugar-derived pluramycin hybrids, which share similarity to the pluramycinone carbocyclic skeleton. This approach involves key steps, namely sequential relay ring-closing enyne metathesis (RRCEM) and Diels-Alder and oxidative aromatization reactions. This methodology opens up interesting possibilities for the synthesis of such hybrids by using diverse sugar units and quinones as starting materials. Ongoing studies in our laboratory will apply this methodology to synthesize various simpler analogues of pluramycinone natural products. In this study, we have successfully synthesized two hybrid molecules, 42 and 45, exhibiting an oxa-tetracyclic framework of pluramycin natural products by successfully controlling the challenging late-stage aromatization reaction with a minor isomer of diene 41 in overall 14 longest linear steps (LLS). In addition to the inherent stability of *C*-glycosidic natural products *in vitro*, the late-stage C–O bond cleavage products derived from the major diene **32** could also serve as novel *C*-glycoside analogues of sugar-quinone hybrids. Hence, these efforts have led to a divergent route for the synthesis of both types of analogues and have potential for further discovery. Efforts to synthesize other different sugar-derived quinone-hybrid molecules and study their biological activities are currently underway in our laboratory.

Experimental section

General information

Unless otherwise noted, all starting materials and reagents were obtained from commercial suppliers and used after further purification. THF was distilled from sodium benzophenone ketyl and toluene from sodium. DCM and DMF were freshly distilled from calcium hydride. All solvents for routine isolation of products and chromatography were of reagent grade and glass distilled. Reaction flasks were dried in an oven at 130 °C for 12 h. Air- and moisture-sensitive reactions were performed under an argon/UHP nitrogen atmosphere. Column chromatography was performed using silica gel (100-200 mesh size) with the indicated solvents. Thin-layer chromatography (TLC) was conducted with Merck silica gel 60 F254 percolated plates (0.25 mm) and visualized with UV, KMnO4, and ceric ammonium molybdate. IR spectra were recorded with PerkinElmer Spectrum One and JASCO V-570 spectrophotometers. Mass spectra were obtained with a Bruker ESI-QTOF spectrometer recorded on Bruker Maxis Impact S No. 282001.0008 and Agilent spectrometers. ¹H NMR spectra were recorded on Bruker 400 MHz and Bruker 500 MHz spectrometers and are reported in ppm using a solvent as an internal standard (CDCl₃ at 7.26 ppm). Proton-decoupled ¹³C NMR spectra were recorded on Bruker 400 MHz and Bruker 500 MHz spectrometers and have been reported using a solvent as an internal standard (CDCl₃ at 77.2 ppm). Optical rotations were measured at 20 °C using an Autopol IV polarimeter.

Experimental data and characterization of products

1-((3a*R*,5*R*,6*S*,6a*R*)-6-((4-Methoxybenzyl)oxy)-2,2-dimethyltetrahydrofuro[2,3-*d*][1,3]dioxol-5-yl)-3-(trimethylsilyl)prop-2-yn-1-ol (17). To a solution of the trimethylsilyl acetylene 16 (0.157 g, 1.60 mmol) in dry THF (7 mL) at -78 °C was added *n*-BuLi (2.0 mL, 1.6 M in hexane, 3.2 mmol) over 5 min, and the reaction mixture was allowed to be stirred at the same temperature for 45 min. Aldehyde 15 (0.2 g, 0.64 mmol) in THF (10 mL) was added to the solution of alkyne at -78 °C, and the reaction was further kept at the same temperature for 1 h, and then stirred at room temperature for 6 h. The reaction mixture was quenched with sat. aqueous NH₄Cl solution, and the organic layer was extracted with EtOAc (3 × 15 mL), washed with brine solution, dried over anhydrous Na₂SO₄, concentrated under reduced pressure, and further purification was done through silica gel column chromatography (1:4 EtOAc/hexane) to obtain 17 (0.064 g, 24% yield, 40% brsm) as a single isomer. **Physical appearance**: Sticky yellow liquid; $R_{\rm f}$: 0.6 (30% EtOAc/ hexane × 2); **IR (neat, cm⁻¹)**: 3468, 2957, 2348, 1613, 1515, 1466, 1375, 1302, 1251, 1215, 1165, 1121, 1077, 1029, 845, 760; [α]_D²⁰: -42.3 (c = 1.00, CHCl₃); ¹H NMR (400 MHz, CDCl₃): δ 7.27 (d, J = 8.5 Hz, 2H), 6.87 (d, J = 8.5 Hz, 2H), 5.94 (d, J = 3.6, 1H), 4.71 (d, J = 8.5 Hz, 1H), 4.57-4.47 (m, 3H), 4.30 (dd, J = 8.4 Hz, 3.6 Hz, 1H), 4.07 (d, J = 3.3 Hz, 1H), 3.79 (s, 3H), 2.55 (br, 1H), 1.51 (s, 3H), 1.31(s, 3H), 0.17(s, 9H); ¹³C NMR (100 MHz, CDCl₃): δ 159.4, 129.4, 129.2, 128.5, 113.8, 112.18, 105.6, 102.5, 90.7, 83.9, 82.4, 72.9, 62.4, 55.2, 26.8, 26.3, -0.24; HRMS (ESI-QTOF): [M + Na]⁺ calcd for C₂₁H₃₀NaO₆Si 429.1709; found 429.1704.

4-((tert-Butyldiphenylsilyl)oxy)-1-((3aR,5R,6S,6aR)-6-((4-methoxybenzyl)oxy)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]-dioxol-5yl)but-2-yn-1-ol (14). To a solution of alkyne 18 (0.47 g, 1.60 mmol) in dry THF (15 mL) at -78 °C was added n-BuLi (2.0 mL, 1.6 M in hexane, 3.2 mmol) over 5 min, and the reaction mixture was allowed to be stirred at the same temperature for 1 h. Aldehyde 15 (0.2 g, 0.64 mmol) in THF (10 mL) was added to the solution of alkyne at -78 °C, and the reaction was further kept at the same temperature for 1 h and then stirred at room temperature for 4 h. The reaction mixture was quenched with sat. aqueous NH4Cl solution, and the organic layer was extracted with EtOAc (3×15 mL), washed with brine solution, dried over anhydrous Na2SO4, concentrated under reduced pressure, and further purification was done through silica gel column chromatography (1:45 EtOAc/hexane) to obtain 14 (0.18 g, 46% yield, 72% brsm) as a single isomer. Physical appearance: Sticky yellow liquid; Rf: 0.5 (30% EtOAc/ hexane × 2); IR (neat, cm⁻¹): 3467, 2933, 2858, 2345, 1613, 1514, 1472, 1428, 1374, 1302, 1215, 1165, 1112, 1075, 1019, 890, 825, 755, 704, 614, 506; $[\alpha]_{D}^{20}$: -37.4 (*c* = 1.00, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.71-7.69 (m, 4H), 7.43-7.36 (m, 6H), 7.23 (d, J = 8.6 Hz, 2H), 6.83 (d, J = 8.6 Hz, 2H), 5.95 (d, J = 3.6 Hz, 1H), 4.70 (d, J = 7.8 Hz, 1H), 4.57 (d, J = 3.6 Hz, 1H), 4.53 (d, J = 10.9 Hz, 1H), 4.44 (d, J = 10.9 Hz, 1H), 4.35 (d, J = 1.6 Hz, 1H), 4.34(d, J = 1.6 Hz, 1H), 4.23 (dd, J = 8.3 Hz, 3.2 Hz, 1H), 4.01(d, J = 3.2 Hz, 1H), 3.75 (s, 3H), 2.42 (br, 1H), 1.52 (s, 3H), 1.33 (s, 3H), 1.05 (s, 9H); ¹³C NMR (100 MHz, CDCl₃): δ 159.5, 135.7, 135.7, 133.0, 130.0, 129.7, 129.3, 127.9, 113.9, 112.3, 105.7, 84.4, 83.8, 82.6, 82.2, 82.0, 72.7, 62.0, 55.3, 52.7, 27.0, 26.8, 26.5, 19.2; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for C35H42NaO7Si 625.2596; found 625.2592.

5-((3aR,5R,6S,6aR)-6-((4-Methoxybenzyl)oxy)-2,2-dimethyltetrahydrofuro[2,3-*d*][1,3]dioxol-5-yl)-11,11-dimethyl-10,10-diphenyl-2,4,9-trioxa-10-siladodec-6-yne (19). To a solution of 14 (0.15 g, 0.25 mol) in CH₂Cl₂ (10 mL) at 0 °C was added DIPEA (0.12 g, 0.99 mmol) followed by freshly prepared MOMCl (0.82 mL, 3 M in toluene). The reaction was monitored by TLC, and after 20 h, the reaction mixture was quenched with water (10 mL). Then the organic layer was extracted with EtOAc (2 × 15 mL), washed with brine solution, dried over anhydrous Na₂SO₄, concentrated under reduced pressure, and further purified *via* silica gel chromatography (1:5 EtOAc/hexane) to obtain 19 (0.062 g, 38% yield, 65% brsm). Physical appearance: Colourless oily liquid; $R_{\rm f}$: 0.5 (25% EtOAc/hexane); **IR** (neat, cm⁻¹): 2932, 2858, 2057, 1737, 1613, 1587, 1471, 1428, 1374, 1302, 1250, 1214, 1163, 1111, 1076, 1030, 946, 917, 824, 757, 704, 624, 505; $[\alpha]_{\rm D}^{20}$: -1.7 (c = 1.00, CHCl₃); ¹H NMR (500 MHz, CDCl₃): δ 7.68 (d, J = 7.5 Hz, 4H), 7.44–7.36 (m, 6H), 7.23 (d, J = 8.6 Hz, 2H), 6.82 (d, J = 8.6 Hz, 2H), 5.95 (d, J = 3.6 Hz, 1H), 4.86 (d, J = 6.7 Hz, 1H), 4.66 (dd, J = 6.7 Hz, 8.8 Hz, 2H), 4.53 (d, J = 3.6 Hz, 1H), 4.50 (d, J = 10.8 Hz, 1H), 4.45 (d, J = 10.8 Hz, 1H), 4.35–4.31(m, 3H), 4.02 (d, J = 3.1 Hz, 1H), 3.75 (s, 3H), 3.39 (s, 3H), 1.63 (br, 1H), 1.52 (s, 3H), 1.32 (s, 3H), 1.03 (s, 9H); ¹³C NMR (125 MHz, CDCl₃) δ 159.3, 135.5, 135.5, 132.8, 132.8, 129.8, 126.7, 129.2, 127.7, 113.7, 111.9, 105.7, 94.2, 84.6, 82.5, 82.2, 81.8, 80.5, 72.5, 65.3, 55.6, 55.2, 52.5, 26.9, 26.6, 26.3, 19.1; HRMS (ESI-QTOF): [M + Na]⁺ calcd for C₃₇H₄₆O₈Si 669.2842 found 669.2854.

((4-(Benzyloxy)-4-((3aR,5R,6S,6aR)-6-((4-methoxybenzyl)oxy)-2,2dimethyltetrahydrofuro[2,3-d][1,3]dioxol-5-yl)but-2-yn-1-yl) oxy)(tert-butyl)diphenylsilane (20). NaH (30 mg, 60% in mineral oil, 0.75 mmol) was charged into a flame dried twoneck round bottomed flask and diluted with anhydrous DMF (7 mL). After cooling down to 0 °C, a solution of alcohols 14 (0.3 g, 0.50 mmol) in DMF (10 mL) was added in a drop-wise manner, and the resulting suspension was stirred at the same temperature for 40 min. Finally, benzyl bromide (0.09 mL, 0.75 mmol) was added, and the resulting mixture was stirred at room temperature over 12 h. After complete consumption of the starting material, the reaction was quenched with saturated NH₄Cl solution, and the product was extracted with $(2 \times$ 10 mL). The combined organic layer was washed with water, dried over anhydrous Na₂SO₄ and then concentrated to obtain the crude product. Purification was done through silica gel column chromatography (1:20 EtOAc/hexane) to obtain the benzylated compound 20 (70%, 0.245 g). Physical appearance: Sticky colourless liquid; R_f: 0.8 (20% EtOAc/hexane); IR (neat, cm⁻¹): 3071, 3015, 2933, 2858, 1612, 1588, 1514, 1471, 1427, 1374, 1303, 1251, 1 216 1164, 1174, 1112, 1078, 1035, 936, 910, 823, 758, 703, 667, 614, 505; $[\alpha]_{\rm D}^{20}$: -2.3 (c = 1.00, CHCl₃); ¹H **NMR (500 MHz, CDCl₃)** δ 7.73 (d, J = 7.2 Hz, 4H), 7.46–7.43 (m, 2H), 7.41-7.38 (m, 6H), 7.35-7.32 (m, 2H), 7.28 (d, J = 7.1 Hz, 1H), 7.24 (d, J = 8.6 Hz, 2H), 6.84 (d, J = 8.6 Hz, 2H), 5.99 (d, J = 3.7 Hz, 1H), 5.78 (d, J = 12.1 Hz, 1H), 4.60 (d, J = 12.1 Hz, 1H), 4.55-4.47 (m, 4H), 4.42 (dd, J = 3.1 Hz, 8.5 Hz, 1H), 4.38-4.37 (m, 2H), 4.07 (d, J = 3.21 Hz, 1H), 3.77 (s, 3H), 1.54 (s, 3H), 1.34 (s, 3H), 1.08 (s, 9H); ¹³C NMR(125 MHz, CDCl₃): δ 159.2, 137.7, 135.5, 135.4, 132.8, 132.8, 129.8, 129.5, 129.3, 128.1, 127.9, 127.7, 127.7, 127.4, 113.6, 111.8, 105.8, 85.0, 82.4, 82.3, 81.7, 81.0, 72.4, 70.7, 68.6, 55.1, 52.5, 26.8, 26.6, 26.3, 19.1; **HRMS (ESI-QTOF)**: $[M + K]^+$ calcd for C₄₂H₄₈KO₇Si 731.2797; found 731.2801.

(3aR,5S,6S,6aR)-5-(1-(Benzyloxy)-4-((tert-butyldiphenyl-silyl)oxy)but-2-yn-1-yl)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-6-ol (13). To a solution of 4-methoxybenzyl ether 20 (0.24 g, 0.34 mmol) in CH₂Cl₂/H₂O (20 mL 10:1) cooled to 0 °C was added 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) (0.19 g, 0.85 mmol) and the solution was stirred at 25 °C for 8 h. The reaction mixture was quenched with sat. NaHCO₃

(20 mL) and the mixture was extracted with EtOAc (20 mL \times 3). The organic layer was washed with water and brine solution, dried over Na₂SO₄, and then concentrated under reduced pressure to obtain the crude product, which was further purified by silica gel column chromatography (1:4 EtOAc/hexane) to obtain alcohol 13 (70%, 0.138 g). Physical appearance: Sticky colourless liquid; Rf: 0.2 (30% EtOAc/hexane); IR (neat, cm⁻¹): 3463, 2932, 2858, 1961, 1471, 1454, 1428, 1374, 1313, 1259, 1216, 1163, 1112, 1070, 1013, 956, 887, 854, 823, 754, 702, 614, 702, 614, 505; $[\alpha]_{D}^{20}$: +36.5 (c = 1.00, CHCl₃); ¹H NMR (400 MHz, CDCl₃): δ 7.76 (d, J = 6.8 Hz, 4H), 7.48–7.41 (m, 6H), 7.37-7.31 (m, 5H), 6.0 (d, J = 3.5 Hz, 1H), 4.79 (d, J = 11.7 Hz, 1H), 4.57(d, J = 11.8 Hz, 1H), 4.49–4.42 (m, 4H), 4.28–4.25 (m, 2H), 2.66 (br, 1H), 1.52 (s, 3H), 1.34 (s, 3H), 1.10 (s, 9H); ¹³C **NMR** (100 MHz, CDCl₃): δ 136.9, 135.4, 132.8, 129.8, 128.3, 128.1, 127.7, 127.7, 113.7, 111.7, 105.2, 86.2, 84.681.6, 80.3, 75.7, 70.6, 67.9, 52.5, 26.7, 26.5, 26.2, 19.0; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for $C_{34}H_{40}NaO_6Si$ 595.2476; found 595.2486.

(E)-Ethyl-3-(((3aR,5R,6S,6aR)-5-(1-(benzyloxy)-4-((tert-butyldiphenylsilyl)oxy)but-2-yn-1-yl)-2,2-dimethyltetrahydrofuro-[2,3d[[1,3]dioxol-6-yl)oxy)acrylate (21). To a solution of alcohol 13 (0.32 g, 0.56 mmol) in anhydrous CH₂Cl₂ (20 mL) was added ethyl propiolate (62 µL, 0.62 mmol) under N2 and stirred for 5 min. Then, N-methyl morpholine (56.6 µL, 0.56 mmol) was added at 0 °C using a micro syringe. The resulting mixture was stirred for 5 h. The reaction mixture was concentrated under reduced pressure and purified by silica gel chromatography (1:10 EtOAc/hexane) to obtain ester 21 (0.25 g, 65%). Physical appearance: Sticky colourless liquid; Rf: 0.6 (20% EtOAc/ hexane); IR (neat, cm⁻¹): 2933, 2861, 1712, 1624, 1515, 1463, 1371, 1329, 1253, 1217, 1136, 1039, 966, 852, 824, 757, 702, 610, 505; $[\alpha]_{D}^{20}$: +14.5 (c = 1.00, CHCl₃); ¹H NMR (500 MHz, CDCl₃): δ 7.72–7.69 (m, 4H), 7.45–7.38 (m, 6H), 7.38–7.37 (m, 3H), 7.33 (t, J = 7.6 Hz, 2H), 7.30 (d, J = 12.7 Hz, 1H), 5.96 (d, J = 3.81 Hz, 1H), 5.30 (d, J = 12.7 Hz, 1H), 4.90 (d, J = 11.8 Hz, 1H), 4.55 (d, J = 11.8 Hz, 1H), 4.50 (d, J = 3.8 Hz, 1H), 4.45-4.42 (m, 2H), 4.43–4.37 (m, 3H), 4.14(qt, J = 7.1 Hz, 2H), 1.32 (s, 3H), 1.25 (t, J = 7.9 Hz, 3H), 1.07 (s, 9H); ¹³C NMR (125 MHz, CDCl₃): δ 166.9, 160.0, 137.4, 135.5, 135.5, 132.8, 132.8, 129.8, 128.2, 127.9, 127.7, 127.7, 127.6, 112.4, 105.5, 98.8, 86.0, 83.6, 81.4, 81.2, 79.7, 70.7, 67.6, 59.9, 52.4, 26.6, 26.6, 26.3, 19.0, 14.2; HRMS (ESI-QTOF): $[M + K]^+$ calcd for $C_{39}H_{46}KO_8Si$ 709.2594; found 709.2592.

(*E*)-3-(((3aR,5*R*,65,6aR)-5-(1-(Benzyloxy)-4-((*tert*-butyldiphenylsilyl)oxy)but-2-yn-1-yl)-2,2-dimethyltetrahydrofuro[2,3-*d*][1,3] dioxol-6-yl)oxy)prop-2-en-1-ol (22). A solution of DIBAL-H {1 M in toluene} (0.6 mL, 0.60 mmol) was added *via* a syringe to a stirred mixture of ester 21 (160 mg, 0.238 mmol) in Et₂O (5.0 mL) at -78 °C. After 1 h, the reaction flask was warmed to -40 °C and further stirred for 4 h. The reaction mixture was quenched using sat. aqueous solution of Rochelle's salt, and the stirring was continued for 1 h. The reaction mixture was then extracted with EtOAc (20 mL × 3), and the combined organic layers were dried over Na₂SO₄ and concentrated under reduced pressure, and further purified by column chromatography using silica gel (1:3 EtOAc/hexanes) to obtain the allylic alcohol 22 (128 mg, 85%). Physical appearance: Sticky colourless oil; $R_{\rm f}$: 0.4 (25% EtOAc/hexanes); IR (neat, cm⁻¹): 3485, 2932, 2861, 1961, 1889, 1825, 1667, 1651, 1455, 1428, 1373, 1306, 1260, 1216, 1165, 1023, 939, 854, 739, 702, 613, 506; $[\alpha]_D^{20}$: + 79.9 (c = 0.50, CHCl₃); ¹H NMR (400 MHz, CDCl₃): δ 7.75–7.69 (m, 4H), 7.48–7.26 (m, 11H), 6.31 (d, J = 12.7 Hz, 1H), 5.96 (d, J = 3.8 Hz, 1H), 5.13 (dt, J = 12.7, 7.3 Hz, 1H), 4.76 (d, J = 11.8 Hz, 1H), 4.56 (dd, J = 10.1, 8.0 Hz, 2H), 4.47–4.30 (m, 5H), 3.97 (d, J = 7.2 Hz, 2H), 1.54 (s, 3H), 1.32 (s, 3H), 1.08 (s, 9H); ¹³C NMR (100 MHz, CDCl₃) δ 147.9, 137.7, 135.7, 135.6, 133.0, 132.9, 130.0, 128.4, 128.1, 127.9, 127.9, 127.7, 112.3, 105.8, 105.7, 85.6, 82.3, 81.7, 81.6, 80.5, 70.8, 68.1, 60.3, 52.7, 26.9, 26.8, 26.5, 19.3; HRMS (ESI-QTOF): [M + K]⁺ calcd for C₃₇H₄₄KO₇Si 667.2488; found 667.2487

((4-((3aR,5R,6S,6aR)-6-(((E)-3-(Allyloxy)prop-1-en-1-yl)oxy)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-5-yl)-4-(benzyloxy)but-2-yn-1-yl)oxy)(tertbutyl)diphenylsilane (12). A flame dried two-neck round-bottomed flask was charged with NaH (10 mg, 0.24 mmol, 60% in mineral oil) and anhydrous DMF (5 mL) was added. After cooling to 0 °C, a solution of alcohol 21 (0.1 g, 0.16 mmol) in DMF (5 mL) was added in a drop-wise manner and the resulting solution was stirred for 40 min at the same temperature. Finally, allyl bromide (20.7 µL, 0.24 mmol) was added at 0 °C using a micro syringe, and the resulting mixture was allowed to be stirred at room temperature for 8 h. The reaction was quenched with saturated NH₄Cl solution, and work-up was done with EtOAc to obtain the crude mixture. Purification was done through silica gel column chromatography (1:7 EtOAc/hexane) to obtain the RRCEM precursor 12 (42 mg, 40%) and the minor compound 23 (31 mg, 30%).

Data for compound (12). Physical appearance: Sticky colourless oil; $R_{\rm f}$: 0.6 (20% EtOAc/hexane); IR (neat, cm⁻¹): 3077, 2932, 2867, 1653, 1456, 1429, 1374, 1261, 1217, 1164, 1114, 1070, 1020, 936, 856, 826, 741, 703, 614, 506; $[\alpha]_{D}^{20}$: + 18.7 (c = 0.5, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.71 (dt, J = 8.0, 1.8 Hz, 4H), 7.45–7.35 (m, 8H), 7.35–7.27 (m, 3H), 6.30 (d, J = 12.7 Hz, 1H), 5.95 (d, J = 3.8 Hz, 1H), 5.93–5.83 (m, 1H), 5.25 (dd, J = 17.2, 1.6 Hz, 1H), 5.17 (dd, J = 10.4, 1.4 Hz, 1H), 5.05 (dt, J = 12.7, 7.3 Hz, 1H), 4.76 (d, J = 11.9 Hz, 1H), 4.60-4.52 (m, 2H), 4.45-4.39 (m, 2H), 4.36 (s, 2H), 4.33 (d, J = 2.6 Hz, 1H), 3.91 (dd, J = 4.0, 2.8 Hz, 2H), 3.82 (d, J = 7.2 Hz, 2H), 1.53 (s, 3H), 1.32 (s, 3H), 1.07 (s, 9H); ¹³C NMR (100 MHz, CDCl₃) δ 148.4, 135.7, 135.7, 134.9, 133.1, 130.1, 128.5, 128.2, 127.9, 127.9, 127.7, 117.3, 112.4, 105.9, 102.9, 85.7, 82.4, 81.8, 81.6, 80.4, 70.9, 70.8, 68.1, 67.4, 52.7, 26.9, 26.8, 26.5, 19.3; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for C₄₀H₄₈NaO₇Si 691.3063; found 691.3062.

(3aR,5R,6S,6aR)-5-(4-(Allyloxy)-1-(benzyloxy)but-2-yn-1-yl)-6-(((E)-3-(allyloxy)prop-1-en-1-yl)oxy)-2,2-dimethyltetrahydrofuro[2,3-d][1,3] dioxole (23)

Data for compound (23). Physical appearance: Sticky colourless oil; $R_{\rm f}$: 0.7 (30% EtOAc/hexane); IR (neat, cm⁻¹): 3079, 2930, 2866, 1663, 1450, 1429, 1374, 1261, 1217, 1164, 1113, 1072, 1010, 932, 944, 856 826, 826, 741, 703, 645, 614, 502; $[\alpha]_{\rm D}^{20}$: +26.7 (c = 0.5, CHCl₃); ¹H NMR (500 MHz, CDCl₃) δ 7.44–7.26 (m, 5H), 6.38 (d, J = 12.7 Hz, 1H), 5.95 (d, J = 3.7 Hz, 1H), 5.95–5.83 (m, 2H), 5.30 (d, J = 13.5 Hz, 1H), 5.27 (d, J = 14.6 Hz, 1H), 5.22 (d, J = 10.4 Hz, 1H), 5.19 (d, J = 10.4 Hz, 1H), 5.14–5.06 (m, 1H), 4.82 (d, J = 11.9 Hz, 1H), 4.65 (d, J = 11.9 Hz, 1H), 4.56 (d, J = 3.7 Hz, 1H), 4.50–4.42 (m, 2H), 4.41 (d, J = 2.4 Hz, 1H), 4.19 (s, 2H), 4.03 (d, J = 5.5 Hz, 2H), 3.95 (d, J = 5.6 Hz, 2H), 3.88 (d, J = 7.3 Hz, 2H), 1.51 (s, 3H), 1.31 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 148.4, 137.7, 134.8, 134.0, 128.4, 128.1, 127.8, 118.0, 117.35, 112.4, 105.1, 102.9, 82.3, 81.8, 81.5, 71.2, 70.8, 70.7, 68.2, 67.4, 57.4, 26.9, 26.5; HRMS (ESI-QTOF): [M + Na]⁺ calcd for C₂₇H₃₄NaO₇ 493.2206; found 493.2208.

(S)-4-(Benzyloxy)-1-((3aR,5R,6S,6aR)-6-((4-methoxy-benzyl)oxy)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-5-yl)but-2-yn-1-ol (26). To a solution of alkyne 24 (2.13 g, 14.5 mmol) in dry THF (20 mL) at -78 °C was added n-BuLi (9.0 mL, 1.6 M in hexane, 3.2 mmol) over 10 min, and the reaction mixture was allowed to be stirred at the same temperature for 1 h. Aldehyde 15 (3 g, 9.72 mmol) in THF (15 mL) was added to the solution of alkyne at -78 °C, and the reaction was further kept at the same temperature for 1 h, then stirred at room temperature for 4 h. The reaction mixture was quenched with sat. aqueous NH₄Cl solution, and the organic layer was extracted with EtOAc (3×30 mL), washed with brine solution, dried over anhydrous Na₂SO₄, concentrated under reduced pressure, and further purification was done through silica gel column chromatography (1:45 EtOAc/hexane) to obtain alcohols 26 (2.21 g, 50%) and 25 (1.34 g, 30%).

Data for major diastereomers (26). Physical appearance: Sticky yellow liquid; $R_{\rm f}$: 0.5 (30% EtOAc/hexane × 2); IR (neat, cm⁻¹): 3467, 2933, 2858, 2345, 1613, 1514, 1472, 1428, 1374, 1302, 1215, 1165, 1112, 1075, 1019, 890, 825, 755, 704, 614, 506; $[\alpha]_{\rm D}^{20}$: -37.4 (c = 1.00, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.36-7.28 (m, 5H), 7.26 (d, J = 8.5 Hz, 2H), 6.85 (d, J = 8.5 Hz, 2H), 5.97 (d, J = 3.6 Hz, 1H), 4.78 (d, J = 8.1 Hz, 1H), 4.61 (dd, J = 7.4, 3.8 Hz, 2H), 4.57 (s, 2H), 4.48 (d, J = 11.2 Hz, 1H), 4.31 (dd, J = 8.0, 3.3 Hz, 1H), 4.19 (s, 2H), 4.08 (d, J = 3.3 Hz, 1H), 2.54 (brs, 1H), 1.51 (s, 3H), 1.33 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 159.6, 137.5, 129.7, 129.2, 128.6, 128.16 128.0, 114.0, 112.4, 105.7, 83.8, 83.7, 82.6, 82.1, 81.9, 72.5, 71.8, 62.0, 57.5, 55.4, 27.0, 26.5; HRMS (ESI-QTOF): [M + Na]⁺ calcd for C₂₆H₃₀NaO₇ 477.1884; found 477.1888.

(R)-4-(Benzyloxy)-1-((3aR,5R,6S,6aR)-6-((4-methoxybenzyl)oxy)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-5-yl)but-2-yn-1-ol (25)

Data for minor diastereomers (25). Physical appearance: Sticky yellow liquid; $R_{\rm f}$: 0.6 (30% EtOAc/hexane ×2); **IR** (neat, cm⁻¹): 3461, 2989, 2932, 2323, 1720, 1610, 1513, 1454, 1380, 1354, 1300, 1254, 1219, 1164, 1073, 1029, 888, 839, 756, 699, 666, 636, 590, 517; $[\alpha]_{\rm D}^{20}$: -45.80 (c = 2.00, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.34-7.27 (m, 5H), 7.25 (d, J = 8.6 Hz, 2H), 6.84 (d, J = 8.6 Hz, 2H), 6.01 (d, J = 3.8 Hz, 1H), 4.80-4.73 (m, 1H), 4.63 (d, J = 11.1 Hz, 1H), 4.59 (d, J = 3.8 Hz, 1H), 4.56 (s, 2H), 4.49 (d, J = 11.1 Hz, 1H), 4.29-4.22 (m, 2H), 4.16 (d, J = 1.4 Hz, 2H), 3.75 (s, 3H), 3.46 (d, J = 9.2 Hz, 1H), 1.48 (s, 3H), 1.31 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 159.8, 137.5, 130.0, 128.6, 128.2, 128.0, 114.2, 112.1, 105.7, 85.1, 83.4, 82.0, 81.8,

81.1, 72.5, 71.8, 61.5, 57.5, 55.4, 27.0, 26.4; **HRMS (ESI-QTOF)**: $[M + Na]^+$ calcd for $C_{26}H_{30}NaO_7$ 477.1884; found 477.1867.

(3aR,5R,6S,6aR)-5-(1,4-Bis(benzyloxy)but-2-yn-1-yl)-6-((4-methoxybenzyl)oxy)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxole (27). NaH (660 mg, 60% in mineral oil, 16.5 mmol) was charged into a flame dried two-neck round-bottomed flask and diluted with anhydrous DMF (15 mL). After cooling down to 0 °C, a solution of 26 (5 g, 11.0 mmol) in DMF (50 mL) was added in a drop-wise manner, and the resulting suspension was stirred at the same temperature for 40 min. Finally, benzyl bromide (1.95 mL, 16.5 mmol) was added and the resulting mixture was stirred at room temperature over 12 h. After complete consumption of the starting material, the reaction mixture was quenched with saturated NH4Cl solution and the product was extracted with EtOAc (3×50 mL). The combined organic layer was washed with water, dried over anhydrous Na₂SO₄ and then concentrated to obtain the crude product. Purification was done through silica gel column chromatography (1:10 EtOAc/ hexane) to obtain the benzylated compound 27 (72%, 4.35 g). Physical appearance: Sticky colourless liquid; Rf: 0.7 (20% EtOAc/hexane); IR (neat, cm⁻¹): 3071, 3015, 2933, 2858, 1612, 1588, 1514, 1471, 1427, 1374, 1303, 1251, 1216, 1164, 1174, 1112, 1078, 1035, 936, 910, 823, 758, 703, 667, 614, 505; $[\alpha]_{\rm D}^{20}$: -35.3 (*c* = 1.00, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.45–7.26 (m, 10H), 7.18 (d, J = 8.6 Hz, 2H), 6.83 (d, J = 8.6 Hz, 2H), 5.97 (d, J = 3.6 Hz, 1H), 4.90 (d, J = 11.3 Hz, 1H), 4.69–4.61 (m, 3H), 4.61–4.42 (m, 4H), 4.38 (dd, J = 9.1, 3.0 Hz, 1H), 4.31 (d, J = 1.4 Hz, 2H), 4.09 (d, J = 2.9 Hz, 1H), 3.78 (s, 3H), 1.53 (s, 3H), 1.34 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 139.2, 131.5, 123.8, 123.3, 77.2, 77.0, 76.7, 59.1, 39.4, 26.2, 25.5, 17.5, 16.1; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for $C_{33}H_{36}NaO_7$ 567.2354; found 567.2353.

(3aR,5S,6S,6aR)-5-(1,4-Bis(benzyloxy)but-2-yn-1-yl)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-6-ol (28). To a solution of the 4-methoxybenzyl ether 27 (2.7 g, 4.9 mmol) in CH_2Cl_2/H_2O (50 mL 10:1) cooled to 0 °C was added DDQ (2.82 g, 12.4 mmol) and the solution was stirred at 25 °C for 5 h. The reaction mixture was quenched with sat. NaHCO₃ (20 mL) which was added at 0 °C, and the mixture was extracted with ethyl acetate (20 mL \times 3). The organic layer was washed with water, followed by brine, dried over NaSO4, and then concentrated to obtain the crude product. The crude product was purified through silica gel column chromatography (1:3 EtOAc/ hexane) to obtain alcohol 28 (80%, 1.5 g). Physical appearance: Sticky colourless liquid; Rf: 0.25 (30% EtOAc/hexane); IR (neat, cm⁻¹): 3540, 2932, 2858, 1961, 1471, 1454, 1428, 1374, 1313, 1259, 1216, 1163, 1112, 1070, 1013, 956, 887, 854, 823, 754, 702, 614, 702, 614, 505; $[\alpha]_D^{20}$: +38.5 (c = 1.00, CHCl₃); ¹H NMR (500 MHz, CDCl₃) δ 7.46-7.26 (m, 10H), 6.02 (d, J = 3.6 Hz, 1H), 4.90 (d, J = 11.8 Hz, 1H), 4.69 (d, J = 11.8 Hz, 1H), 4.63 (s, 2H), 4.56 (d, J = 6.2 Hz, 1H), 4.50 (d, J = 3.6 Hz, 1H), 4.40–4.33 (m, 2H), 4.27 (d, J = 1.3 Hz, 2H), 1.53 (s, 3H), 1.34 (s, 3H); ¹³C NMR (125 MHz, CDCl₃) δ 137.0, 136.9, 128.4, 128.3, 128.1, 128.0, 127.9, 127.8, 111.8, 105.3, 84.7, 83.8, 81.8, 81.6, 77.2, 77.0, 76.7, 75.8, 71.7, 71.0, 68.1, 57.2, 26.7, 26.2; HRMS (ESI-QTOF): [M + Na]⁺ calcd for C₂₅H₂₈NaO₆ 447.1774; found 447.1778.

Ethyl(E)-3-(((3aR,5R,6S,6aR)-5-(1,4-bis(benzyloxy)but-2-yn-1yl)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-6-yl) oxy)acrylate (29). To a solution of alcohol 28 (1 g, 2.30 mmol) in anhydrous CH₂Cl₂ (20 mL) was added ethyl propiolate (0.25 mL, 2.53 mmol) under N2 and stirred for 5 min. Then, N-methyl morpholine (2.33 mL, 2.30 mmol) was added at 0 °C using a micro syringe. The resulting mixture was stirred for 5 h. The reaction mixture was concentrated and purified by silica gel chromatography (1:10 EtOAc/hexane) to obtain ester 29 (0.82 g, 68%). Physical appearance: Sticky colourless liquid; Rf: 0.5 (20% EtOAc/hexanes); IR (neat, cm^{-1}): 3032, 2933, 2861, 1712, 1624, 1515, 1463, 1371, 1329, 1253, 1217, 1136, 1039, 966, 852, 824, 757, 702, 610, 505; $[\alpha]_{D}^{20}$: +24.5 (*c* = 1.00, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.51 (d, J = 12.7 Hz, 1H), 7.43-7.23 (m, 10H), 5.99 (d, J = 3.8 Hz, 1H), 5.37 (d, J = 12.7 Hz, 1H), 4.84 (d, J = 11.9 Hz, 1H), 4.66 (d, J = 11.9 Hz, 1H), 4.54 (ddd, J = 10.3, 6.2, 2.3 Hz, 5H), 4.47 (t, J = 4.7 Hz, 1H),4.29-4.18 (m, 2H), 4.14 (q, J = 7.1 Hz, 2H), 1.53 (s, 3H), 1.32 (s, 3H), 1.25 (t, J = 7.1 Hz, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 166.9, 160.1, 137.3, 137.1, 128.3, 128.2, 127.9, 127.8, 127.6, 112.5, 105.5, 98.9, 83.9, 83.6, 81.5, 81.4, 81.3, 77.3, 77.0, 76.6, 71.6, 71.0, 67.8, 59.9, 57.1, 26.6, 26.2, 14.2; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for C₃₀H₃₄NaO₈ 545.2146; found 545.2146.

(E)-3-(((3aR,5R,6S,6aR)-5-(1,4-Bis(benzyloxy)but-2-yn-1-yl)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-6-yl)oxy)prop-2-en-1-ol (30). A solution of DIBAL-H {1 M in toluene} (3.82 mL) was added via a syringe to a stirred mixture of ester 29 (0.8 g, 1.53 mmol) in Et_2O (5.0 mL) at -78 °C. After 1 h, the reaction flask was warmed to -40 °C and further stirred for 5 h. The reaction mixture was quenched using a sat. aqueous solution of Rochelle's salt, and the stirring was continued for 1 h. The reaction mixture was then extracted with EtOAc (40 mL \times 2). The combined organic layers were dried over Na2SO4 and concentrated under reduced pressure. The crude product was purified by column chromatography using silica gel (1:25 EtOAc/ hexanes) to obtain the allylic alcohol 30 (585 mg, 80%). Physical appearance: sticky colourless oil; Rf: 0.3 (25% EtOAc/ hexane); IR (neat, cm⁻¹): 3485, 3021, 2932, 2861, 1632, 1455, 1428, 1373, 1306, 1260, 1216, 1165, 1023, 939, 854, 739, 702, 613, 506; $[\alpha]_{D}^{20}$: +79.9 (c = 0.50, CHCl₃); ¹H NMR (400 MHz, **CDCl**₃) δ 7.52–7.15 (m, 10H), 6.37 (d, J = 12.7 Hz, 1H), 5.98 (d, J = 3.8 Hz, 1H), 5.16 (dd, J = 7.1, 5.6 Hz, 1H), 4.84 (d, J = 11.9 Hz, 1H), 4.67 (d, J = 11.9 Hz, 1H), 4.58 (s, 2H), 4.56 (d, J = 3.8 Hz, 1H), 4.50 (d, J = 2.8 Hz, 2H), 4.43 (d, J = 2.4 Hz, 1H), 4.22 (d, J = 0.7 Hz, 2H), 3.95 (d, J = 7.2 Hz, 2H), 1.53 (s, 3H), 1.32 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 147.8, 137.6, 137.2, 128.5, 128.4, 128.1, 128.0, 127.7, 112.3, 105.8, 105.7, 83.1, 82.4, 82.1, 81.9, 81.6, 71.7, 71.1, 68.3, 60.1, 57.3, 26.8, 26.4; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for C₂₈H₃₂NaO₇ 503.2040; found 503.2040.

(3aR,5R,6S,6aR)-6-(((*E*)-3-(Allyloxy)prop-1-en-1-yl)oxy)-5-(1,4-bis (benzyloxy)but-2-yn-1-yl)-2,2-dimethyltetrahydrofuro[2,3-*d*][1,3] dioxole (31). A flame-dried two neck round-bottomed flask was charged with NaH (60 mg, 1.45 mmol, 60% in mineral oil) and anhydrous DMF (15 mL) was added. After cooling to 0 °C, a solution of alcohol 30 (450 mg, 0.936 mmol) in DMF (10 mL) was added in a drop-wise manner, and the resulting solution was stirred for 40 min at the same temperature. Finally, allyl bromide (0.125 mL, 1.45 mmol) was added at 0 °C, and the resulting mixture was stirred to room temperature for 12 h. The reaction was quenched with saturated NH₄Cl solution, and work-up was done with EtOAc to obtain the crude mixture. Purification was done through silica gel column chromatography (1:9 EtOAc/hexane) to obtain the RRCEM precursor 31 (300 mg, 60%). Physical appearance: sticky colourless oil; R_f: 0.5 (20% EtOAc/hexane); IR (neat, cm⁻¹): 3077, 2932, 2867, 1653, 1456, 1429, 1374, 1261, 1217, 1164, 1114, 1070, 1020, 936, 856, 826, 741, 703, 614, 506; $[\alpha]_{D}^{20}$: +28.7 (c = 0.5, CHCl₃); ¹H NMR (500 MHz, CDCl₃) δ 7.41 (d, J = 7.3 Hz, 2H), 7.39–7.30 (m, 7H), 7.28 (d, J = 7.3 Hz, 1H), 6.39 (d, J = 12.7 Hz, 1H), 5.97 (d, I = 3.8 Hz, 1H), 5.89 (ddd, I = 22.8, 10.8, 5.6 Hz, 1H), 5.25 (dd, J = 17.2, 1.4 Hz, 1H), 5.17 (d, J = 10.4 Hz, 1H), 5.11 (dt, J = 12.9, 7.3 Hz, 1H), 4.84 (d, J = 11.9 Hz, 1H), 4.67 (d, J = 11.9 Hz, 1H), 4.57 (s, 3H), 4.49 (d, J = 3.0 Hz, 2H), 4.43 (d, J = 2.5 Hz, 1H), 4.22 (s, 2H), 3.92 (d, J = 5.7 Hz, 2H), 3.83 (d, J = 7.3 Hz, 2H), 1.53 (s, 3H), 1.32 (s, 3H); ¹³C NMR (125 MHz, CDCl₃) δ 148.4, 137.7, 137.4, 134.8, 128.6, 128.4, 128.1, 128.1, 128.0, 127.8, 117.2, 112.4, 105.9, 102.9, 83.2, 82.1, 82.1, 81.9, 81.1, 71.7, 71.2, 70.8, 68.3, 67.3, 57.4, 26.9, 26.5; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for C₃₁H₃₆NaO₇ 543.2368; found 543.2353.

(3aR,3bS,7aR,8aR)-7-(Benzyloxy)-6-(3-(benzyloxy)prop-1-en-2yl)-2,2-dimethyl-3a,3b,7a,8a-tetrahydro-7H-[1,3]di-oxo-lo[4',5':4,5] furo[3,2-b]pyran (32). A solution of the RRCEM precursor 31 (190 mg, 0.36 mmol) in toluene (80 mL) was degassed under argon; the G-II catalyst (21.3 mg, 7 mol%) was added and the solution was stirred at reflux under an argon atmosphere for 30 min. After completion of the reaction, the solution was cooled to room temperature and the solvent was evaporated under reduced pressure. The resulting crude mixture was washed with pentane and purified by column chromatography (1:12 EtOAc/hexane) to obtain the corresponding 1,3-diene 32 (132 mg, 80%). Physical appearance: Sticky colourless oil; R_f: 0.6 (20% EtOAc/hexane); $[\alpha]_{D}^{20}$: +21.82 (*c* = 1.5, CHCl₃); **IR** (neat, cm⁻¹): 3077, 2939, 2867, 1634, 1450, 1429, 1374, 1261, 1217, 1164, 1114, 1070, 1020, 936, 856, 826, 741, 703, 614, 506; ¹H NMR (500 MHz, CDCl₃) δ 7.39-7.27 (m, 10H), 6.86 (s, 1H), 5.89 (d, J = 3.6 Hz, 1H), 5.12 (s, 1H), 5.07 (s, 1H), 4.71 (d, J = 11.5)Hz, 1H), 4.69 (d, J = 3.6 Hz, 1H), 4.63 (d, J = 11.5 Hz, 1H), 4.54-4.51 (m, 1H), 4.48 (d, J = 0.8 Hz, 2H), 4.39 (d, J = 2.0 Hz, 1H), 4.38 (d, J = 1.5 Hz, 1H), 4.21-4.11 (m, 2H), 1.54 (s, 3H), 1.36 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 143.6, 140.2, 138.3, 138.0, 128.5, 128.4, 128.0, 127.9, 127.7, 112.4, 111.7, 109.9, 104.8, 83.8, 74.8, 74.24, 72.0, 71.6, 71.4, 66.8, 26.8, 26.3; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for $C_{27}H_{30}NaO_6$ 473.1935; found 473.1929.

2-((Benzyloxy)((3aR,55,65,6aR)-6-hydroxy-2,2-dimethyltetrahydrofuro[2,3-*d*][1,3]dioxol-5-yl)methyl)-3-((benzyloxy)methyl)anthracene-9,10-dione (36). A mixture of diene 32 (80 mg, 0.177 mmol) and quinone 33 (33.5 g, 0.212 mmol) in toluene (1.5 mL) was heated to 100–110 °C for 24 h. After complete consumption of diene 32, the resulting mixture was concentrated under reduced pressure to give the crude cycloadduct product 34. The crude cycloadduct product was re-dissolved in $CHCl_3$ (7 mL); then Et_3N (0.5 mL) purged with SiO_2 (2 g) was added in one portion and stirred for 1 h at room temperature. The reaction mixture was concentrated and purified by column chromatography (2:5 EtOAc/hexane), affording the aromatized product 36 (60 mg, 56%). Physical appearance: Yellow-orange powder solid; $R_{\rm f}$: 0.4 (30% EtOAc/hexane × 2); IR (KBr) cm⁻¹: 3432, 3077, 2932, 2867, 1456, 1429, 1374, 1261, 1217, 1164, 1114, 1070, 1020, 936, 856, 826, 741, 703, 614, 506; $[\alpha]_{D}^{20}$: +20.7 $(c = 0.5, \text{ CHCl}_3)$; ¹H NMR (500 MHz, CDCl₃) δ 8.61 (s, 1H), 8.35-8.28 (m, 2H), 8.23 (s, 1H), 7.84-7.79 (m, 2H), 7.40-7.20 (m, 10H), 6.03 (d, J = 3.7 Hz, 1H), 5.11 (d, J = 5.8 Hz, 1H), 4.55 (d, J = 2.5 Hz, 1H), 4.54–4.51 (m, 2H), 4.49 (dd, J = 5.5, 2.6 Hz, 1H), 4.48 (dd, J = 11.3, 4.3 Hz, 2H), 4.42 (d, J = 3.7 Hz, 1H), 4.36 (d, J = 12.0 Hz, 1H), 3.86 (d, J = 2.3 Hz, 1H), 1.43 (s, 3H), 1.27 (s, 3H); ¹³C NMR (125 MHz, CDCl₃) δ 182.7, 182.5, 144.0, 143.2, 141.7, 137.0, 136.5, 134.3, 134.2, 133.6, 133.4, 132.9, 128.9, 128.6, 128.5, 128.3, 128.2, 128.1, 128.0, 128.0, 127.3, 127.2, 111.7, 105.0, 84.9, 82.5, 77.3, 77.0, 76.7, 75.4, 73.2, 71.3, 69.4, 26.7, 26.1; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for C37H34NaO8 629.2254; found 629.2252.

6-((S)-(Benzyloxy)((3aR,5S,6S,6aR)-6-hydroxy-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-5-yl)methyl)-7-((benzyloxy)methyl)-1methoxyanthracene-9,10-dione (39). A mixture of diene 32 (50 mg, 0.11 mmol) and quinone 37 (35 mg, 0.13 mmol) in toluene (1.5 mL) was heated to 100 °C for 15 h. After complete consumption of diene 32, the resulting mixture was concentrated under reduced pressure to give the crude cycloadduct product 38. The crude cycloadduct product was re-dissolved in CH₂Cl₂ (10 mL); then Et₃N (0.5 mL) was added at 0 °C and stirred for 2 h at room temperature. The reaction mixture was concentrated and purified by column chromatography (2:5 EtOAc/hexane), affording the aromatized product 39 (35 mg, 50%). Physical appearance: Yellow-orange sticky solid; R_f: 0.5 (30% EtOAc/hexane); IR (KBr, cm⁻¹): 3528, 3423, 2922, 2847, 1752, 1674, 1605, 1591, 1446, 1216, 1163, 1147, 1020, 976, 790, 668; $[\alpha]_{D}^{20}$: +85.40 (c = 0.4, CHCl₃); ¹H NMR (500 MHz, CDCl₃) δ 8.52 (s, 1H), 8.29 (s, 1H), 7.95 (d, J = 7.4 Hz, 1H), 7.70 (t, J = 8.0 Hz, 1H), 7.37–7.31 (m, 5H), 7.28–7.24 (m, 2H), 7.22 (dd, J = 7.4, 5.2 Hz, 3H), 5.80 (d, J = 3.5 Hz, 1H), 5.12 (d, J = 7.2 Hz, 1H), 4.75 (d, J = 12.4 Hz, 1H), 4.57 (s, 2H), 4.52 (dd, J = 12.2, 7.4 Hz, 2H), 4.44 (d, J = 3.5 Hz, 1H), 4.31 (s, 1H), 4.24-4.18 (m, 2H), 4.03 (s, 3H), 1.31 (s, 3H), 1.21 (s, 3H); ¹³C NMR (125 MHz, $CDCl_3$ δ 183.2, 182.4, 160.5, 144.1, 143.7, 137.7, 137.3, 135.9, 135.2, 134.6, 132.5, 128.8, 128.6, 128.4, 128.2, 128.1, 128.0, 128.0, 125.8, 121.6, 120.0, 118.1, 111.8; HRMS (ESI-QTOF): [M + K]⁺ calcd for C₃₈H₃₆O₉ 675.1962; found 675.1962.

6-((*S*)-(Benzyloxy)((3a*R*,5*S*,66*R*)-6-hydroxy-2,2-dimethyl tetrahydrofuro[2,3-*d*][1,3]dioxol-5-yl)methyl)-7-((benzyloxy) methyl)-1-methoxyanthracene-9,10-dione (46). A mixture of diene 32 (30 mg, 0.06 mmol) and quinone 43 (14 mg, 0.08 mmol) in toluene (1 mL) was heated to 100 °C for 24 h. After complete consumption of diene 32, the resulting mixture was concentrated under reduced pressure to give a crude cyclo-adduct product, which was re-dissolved in a mixture of acetone (2.5 mL) and water (5:1) and treated with OsO₄ (1 mol%) and *N*-methylmorpholine *N*-oxide (26.3 µL, 0.24 mmol) at room

temperature. The reaction mixture was then allowed to stir for 8 h. After the consumption of the starting material, the reaction temperature was brought to 0 °C, and an excess of Et₃N (0.5 mL) was added in a drop-wise manner and stirred at rt for 12 h. After completion of the reaction, the solvent was evaporated, and the residue was purified using silica gel column chromatography (1:4 EtOAc/hexane), affording compound 46 (20 mg, 40%). Physical appearance: Yellow-orange sticky solid; $R_{\rm f}$: 0.5 (20% EtOAc/hexane × 2); IR (neat) cm⁻¹: 3427, 2922, 2857, 1674, 1639, 1603, 1456, 1354, 1291, 1212, 1166, 1070, 1015, 914, 885, 863, 760, 699, 607; $\left[\alpha\right]_{\rm D}^{20}$: +34.48 (c = 1.5, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 12.62 (s, 1H), 8.63 (s, 1H), 8.23 (s, 1H), 7.84 (d, J = 7.5 Hz, 1H), 7.70 (t, J = 8.0 Hz, 1H), 7.43-7.37 (m, 3H), 7.36-7.29 (m, 7H), 7.27-7.22 (m, 2H), 6.05 (d, J = 3.7 Hz, 1H), 5.14 (d, J = 5.5 Hz, 1H), 4.56 (d, J = 11.9 Hz, 3H), 4.52–4.47 (m, 3H), 4.44 (d, J = 3.8 Hz, 1H), 4.39 (d, J = 12.0 Hz, 1H), 4.18 (d, J = 3.1 Hz, 1H), 3.92 (s, 1H), 1.44 (s, 3H), 1.30 (s, 4H); ¹³C NMR (100 MHz, CDCl₃) δ 188.1, 182.1, 162.7, 144.3, 142.4, 137.0, 136.9, 136.6, 133.5, 133.4, 133.1, 129.1, 128.8, 128.7, 128.4, 128.3, 128.3, 128.2, 128.1, 124.7, 119.7, 116.3, 111.8, 105.1, 85.1, 82.4, 75.7, 73.4, 71.5, 69.5, 26.9, 26.3; **HRMS (ESI-QTOF):** $[M + Na]^+$ calcd for $C_{37}H_{34}NaO_9$ 645.2047; found 645.2047.

(3aR,5R,6S,6aR)-5-((R)-1,4-Bis(benzyloxy)but-2-yn-1-yl)-6-((4-methoxybenzyl)oxy)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxole (S4). NaH (462 mg, 60% in mineral oil, 11.5 mmol) was charged into a flame dried two-neck round bottomed flask and diluted with anhydrous DMF (20 mL). After cooling down to 0 °C, a solution of alcohol 25 (3.5 g, 7.70 mmol) in DMF (40 mL) was added in a dropwise manner, and the resulting suspension was stirred at the same temperature for 40 min. Finally, benzyl bromide (1.36 mL, 11.5 mmol) was added, and the resulting mixture was stirred at room temperature over 12 h. After complete consumption of the starting material, the reaction mixture was quenched with saturated NH4Cl solution, and the product was extracted with EtOAc (2×40 mL). The combined organic layer was washed with water, dried over anhydrous Na₂SO₄ and then concentrated to obtain the crude product. Purification was done through silica gel column chromatography (1:10 EtOAc/hexane) to obtain the benzylated compound S4 (80%, 3.3 g). Physical appearance: Sticky yellow liquid; R_f : 0.7 (25% EtOAc/hexane); IR (neat, cm⁻¹): = 3461, 2989, 2932, 2227, 1720, 1610, 1584, 1513, 1454, 1380, 1354, 1300, 1254, 1164, 1073, 1029, 839, 756, 699, 666, 636, 590, 517; $[\alpha]_{D}^{20}$: +31.53 (c = 0.5, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.45–7.26 (m, 10H), 7.18 (d, J = 8.6 Hz, 2H), 6.83 (d, J = 8.6 Hz, 2H), 5.97 (d, J = 3.6 Hz, 1H), 4.90 (d, J = 11.3)Hz, 1H), 4.68–4.61 (m, 3H), 4.58 (t, J = 7.7 Hz, 2H), 4.50 (d, J = 11.3 Hz, 1H), 4.46 (d, J = 11.4 Hz, 1H), 4.37 (dd, J = 9.1, 2.9 Hz, 1H), 4.30 (d, J = 1.3 Hz, 2H), 4.09 (d, J = 2.9 Hz, 1H), 3.78 (s, 3H), 1.53 (s, 3H), 1.34 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 159.4, 137.7, 137.6, 129.7, 129.2, 128.5, 128.4, 128.3, 128.0, 127.9, 127.8, 113.9, 112.0, 105.3, 83.9, 83.2, 82.3, 81.3, 80.8, 72.1, 71.4, 70.9, 66.6, 57.6, 55.3, 26.9, 26.4; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for $C_{33}H_{36}NaO_7$ 567.2354; found 567.2353.

(3aR,5S,6S,6aR)-5-((R)-1,4-Bis(benzyloxy)but-2-yn-1-yl)-2,2dimethyltetrahydrofuro[2,3-d][1,3]dioxol-6-ol (S5). To a solution of the 4-methoxybenzyl ether S4 (3 g, 7.0 mmol) in CH₂Cl₂/ H_2O (50 mL 10:1) cooled to 0 °C was added DDQ (4.72 g, 17.5 mmol) and the solution was stirred at 25 °C for 4 h. The reaction mixture was guenched with sat. NaHCO₃ (30 mL) and the mixture was extracted with ethyl acetate (30 mL \times 3). The organic layer was washed with water followed by brine, dried over Na₂SO₄, and then concentrated to obtain the crude product, which was further purified through silica gel column chromatography (1:35 EtOAc/hexane) to obtain the alcohol S5 (90%, 2.1 g). Physical appearance: Sticky colorless liquid; Rf: 0.2 (30% EtOAc/hexane); IR (neat, cm⁻¹): 3471, 3089, 2988, 2931, 2861, 2237, 1957, 1723, 1630, 1606, 1496, 1454, 1375, 1354, 1315, 1216, 1164, 1081, 1020, 947, 884, 858, 750, 699, 638, 605, 540, 520; $[\alpha]_{D}^{20}$: -52.56 (c = 3.0, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.39–7.28 (m, 10H), 5.98 (d, J = 3.6 Hz, 1H), 4.87 (d, J = 11.7 Hz, 1H), 4.65–4.59 (m, 4H), 4.50 (d, J = 3.6 Hz, 1H), 4.45 (d, J = 2.2 Hz, 1H), 4.28 (dd, J = 6.5, 2.1 Hz, 3H), 1.68 (br s, 1H), 1.50 (s, 3H), 1.32 (s, 3H); ¹³C NMR (100 MHz, $CDCl_3$) δ 137.3, 136.6, 128.8, 128.6, 128.4, 128.3, 128.1, 112.0, 105.3, 84.9, 84.4, 81.9, 81.1, 75.5, 71.9, 71.6, 67.8, 57.5, 27.0, 26.3; HRMS (ESI-QTOF): $[M + K]^+$ calcd for $C_{25}H_{28}KO_6$ 463.1482; found 463.1481.

Ethyl(E)-3-(((3aR,5R,6S,6aR)-5-((R)-1,4-bis(benzyloxy)but-2-yn-1yl)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-6-yl) oxy)acrylate (S6). To a solution of alcohol S5 (1 g, 2.3 mmol) in anhydrous CH₂Cl₂ (20 mL) was added ethyl propiolate (0.25 mL, 2.53 mmol) under N2 and stirred for 5 min. Then, N-methyl morpholine (0.23 mL, 2.3 mmol) was added at 0 °C. The resulting mixture was stirred for 12 h. The reaction mixture was concentrated and purified by silica gel chromatography (1:12 EtOAc/hexane) to obtain the ester S6 (0.92 g, 75%). Physical appearance: Sticky colourless liquid; Rf: 0.5 (20% EtOAc/ hexanes); IR (neat, cm⁻¹): 3030, 2980, 2850, 1713, 1645, 1626, 1496, 1454, 1374, 1324, 1285, 1260, 1216, 1194, 1166, 1138, 1067, 1048, 1024, 949, 907, 884, 853, 755, 699, 667, 644, 519; $[\alpha]_{D}^{20}$: +87.41 (c = 1.5, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.42-7.27 (m, 10H), 5.93 (d, J = 3.7 Hz, 1H), 5.33 (d, J = 12.2 Hz, 1H), 4.80 (d, J = 12.2 Hz, 1H), 4.65 (s, 2H), 4.54 (d, J = 3.8 Hz, 1H), 4.48 (t, J = 7.2 Hz, 2H), 4.43-4.33 (m, 2H), 4.29 (d, J = 1.4 Hz, 2H), 4.23-4.13 (m, 2H), 1.51 (s, 3H), 1.31 (s, 3H), 1.28 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 167.2, 160.6, 137.4, 136.8, 128.7, 128.5, 128.5, 128.3, 128.24, 128.0, 112.6, 105.2, 99.0, 83.6, 83.0, 82.9, 82.1, 80.5, 71.6, 70.9, 65.5, 60.1, 57.5, 26.7, 26.4, 14.4; HRMS (ESI-QTOF): $[M + K]^+$ calcd for C₃₀H₃₄KO₈ 561.1851; found 561.1851.

(E)-3-(((3aR, 5R, 6S, 6aR)-5-(((R)-1,4-Bis(benzyloxy)but-2-yn-1-yl)-2,2-dimethyltetrahydrofuro[2,3-*d*][1,3]dioxol-6-yl)oxy) prop-2-en-1-ol (S7). A solution of DIBAL-H {1M in toluene} (10.25 mL) was added *via* a syringe to a stirred mixture of ester S6 (2 g, 4.1 mmol) in Et₂O (25 mL) at -78 °C. After 1 h, the reaction flask was warmed to -40 °C and further stirred for 2 h. The reaction mixture was quenched using a sat. aqueous solution of Rochelle's salt, and the stirring was continued for 1 h. The reaction mixture was then extracted with EtOAc (30 mL × 2). The combined organic layers were dried over Na₂SO₄ and concentrated under reduced pressure. The crude product was purified by column chromatography using silica gel chromatography (1:3 EtOAc/hexanes) to obtain the allylic alcohol S7 (1.6 g, 90%). Physical appearance: Sticky colourless oil; Rf: 0.35 (20% EtOAc/hexane); IR (neat, cm⁻¹): 3475, 3064, 2989, 2935, 2345, 1876, 1808, 1670, 1652, 1496, 1454, 1375, 1310, 1218, 1167, 1107, 1073, 1025, 941, 854, 755, 699, 638, 517; $\left[\alpha\right]_{D}^{20}$: $-48.37 (c = 5.0, CHCl_3);$ ¹H NMR (500 MHz, CDCl₃) δ 7.45–7.22 (m, 10H), 6.32 (d, J = 12.6 Hz, 1H), 5.96–5.85 (m, 2H), 5.27 (d, J = 17.2 Hz, 1H), 5.19 (d, J = 10.4 Hz, 1H), 5.16–5.05 (m, 1H), 4.82 (d, J = 11.3 Hz, 1H), 4.64 (s, 2H), 4.58 (d, J = 3.3 Hz, 1H), 4.49 (d, J = 11.3 Hz, 1H), 4.44 (d, J = 9.4 Hz, 1H), 4.40–4.33 (m, 2H), 4.28 (s, 2H), 3.95 (d, I = 5.3 Hz, 2H), 3.87 (d, I = 7.0 Hz, 2H), 1.51 (s, 3H), 1.31 (s, 3H); ¹³C NMR (125 MHz, CDCl₃) δ 148.7, 137.5, 137.4, 134.9, 128.6, 128.5, 128.4, 128.0, 117.2, 112.4, 105.3, 102.7, 83.5, 83.3, 82.1, 81.1, 80.8, 77.2, 71.6, 71.0, 70.8, 67.3, 66.0, 57.6, 26.9, 26.5; HRMS (ESI-QTOF): [M + Na] calcd for C₂₈H₃₂NaO₇ 503.2040; found 503.2040.

(3aR,5R,6S,6aR)-6-(((E)-3-(Allyloxy)prop-1-en-1-yl)oxy)-5-((R)-1,4bis(benzyloxy)but-2-yn-1-yl)-2,2-dimethyltetrahydrofuro[2,3-d][1,3] dioxole (S8). A flame-dried two-neck round-bottomed flask was charged with NaH (37.4 mg, 0.93 mmol, 60% in mineral oil) and anhydrous DMF (7 mL) was added. After cooling to 0 °C, a solution of alcohol S7 (300 mg, 0.62 mmol) in DMF (5 mL) was added in a drop-wise manner, and the resulting solution was stirred for 30 min at the same temperature. Finally, allyl bromide (82 μ L, 0.95 mmol) was added, and the resulting mixture was stirred to room temperature for 12 h. The reaction was quenched with saturated NH₄Cl solution, and work-up was done with EtOAc to obtain the crude mixture. Purification was done through silica gel column chromatography (1:10 EtOAc/hexane) to obtain the RRCEM precursor S8 (240 mg, 70%). Physical appearance: Sticky colourless oil; Rf: 0.6 (20% EtOAc/hexane); IR (neat, cm⁻¹): 3031, 2938, 2850, 2345, 1725, 1493, 1452, 1386, 1216, 1163, 1097, 1072, 1017, 946, 883, 885, 756, 699, 670, 521; $[\alpha]_{D}^{20}$: 14.63 (c = 0.6, CHCl₃); ¹H NMR (500 MHz, CDCl₃) δ 7.41–7.27 (m, 10H), 6.32 (d, J = 12.6 Hz, 1H), 5.95-5.87 (m, 2H), 5.27 (d, J = 17.2 Hz, 1H), 5.19 (d, J = 10.4 Hz, 1H), 5.16–5.07 (m, 1H), 4.82 (d, J = 11.3 Hz, 1H), 4.64 (s, 2H), 4.58 (d, J = 3.3 Hz, 1H), 4.49 (d, J = 11.3 Hz, 1H), 4.44 (d, J = 9.4 Hz, 1H), 4.40-4.33 (m, 2H), 4.28 (s, 2H), 3.95 (d, J = 5.3 Hz, 2H), 3.87 (d, J = 7.0 Hz, 2H), 1.51 (s, 3H), 1.31 (s, 3H); ¹³C NMR (125 MHz, CDCl₃) δ 148.6, 137.4, 137.2, 134.7, 128.4, 128.3, 128.2, 127.8, 117.1, 112.2, 105.1, 102.6, 83.3, 83.1, 81.9, 80.9, 80.6, 71.4, 70.8, 70.6, 67.2, 65.8, 57.4, 26.7, 26.3; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for $C_{31}H_{36}NaO_7$ 543.2312; found 543.2312.

(3aR,3bS,7R,7aR,8aR)-7-(Benzyloxy)-6-(3-(benzyloxy)prop-1-en-2yl)-2,2-dimethyl-3a,3b,7a,8a-tetrahydro-7*H*-[1,3]dioxolo[4',5':4,5] furo[3,2-*b*]pyran (41). A solution of the RRCEM precursor S8 (200 mg, 0.38 mmol) in toluene (80 mL) was degassed under argon; the G-II catalyst (22.5 mg, 7 mol%) was added in one portion and the solution was stirred at reflux under an argon atmosphere for 2 h. After completion of the reaction, the solution was cooled to room temperature, and then the reaction

mixture was evaporated to dryness. The resulting crude mixture was washed with pentane and purified by column chromatography (1:12 EtOAc/hexane) to obtain the corresponding 1,3-diene 41 (160 mg, 85%). Physical appearance: Sticky colourless oil; $R_{\rm f}$: 0.5 (20% EtOAc/hexane); $[\alpha]_{\rm D}^{20}$: +21.82 $(c = 1.5, CHCl_3)$; IR (neat, cm⁻¹): 3037, 2983, 2928, 1725, 1637, 1496, 1454, 1380, 1379, 1283, 1264, 1215, 1164, 1082, 1024, 890, 865, 843, 756, 699, 666, 604; ¹H NMR (400 MHz, CDCl₃) δ 7.40-7.26 (m, 10H), 6.63 (s, 1H), 6.03 (d, J = 3.7 Hz, 1H), 5.20 (d, J = 1.4 Hz, 1H), 5.07 (d, J = 1.4 Hz, 1H), 4.76 (d, J = 11.5 Hz, 1H), 4.69 (dd, J = 3.7, 0.9 Hz, 1H), 4.64 (dd, J = 5.0, 2.3 Hz, 1H), 4.59 (s, 1H), 4.53 (d, J = 17.7 Hz, 1H), 4.45 (d, J = 25.8 Hz, 1H), 4.38 (d, J = 7.8 Hz, 1H), 4.24 (d, J = 12.2 Hz, 1H), 4.06 (d, J = 12.3 Hz, 1H), 1.54 (s, 3H), 1.36 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 142.1, 140.4, 138.3, 137.9, 128.4, 128.4, 128.1, 128.0, 127.7, 127.7, 113.5, 112.7, 112.3, 104.8, 83.6, 78.4, 72.3, 72.3, 71.7, 70.4, 67.6, 26.8, 26.4; HRMS (ESI-QTOF): [M + Na]⁺ calcd for C₂₇H₃₀NaO₆ 473.1894; found 473.1893.

(8R,8aR,9aR,12aR,12bS)-8-(Benzyloxy)-7-((benzyloxy)methyl)-11,11-dimethyl-8a,9a,12a,12b-tetrahydro-8H-[1,3]dioxolo-[4',5':4,5] furo[3,2-b]naphtho[2,3-h]chromene-5,14-dione (42). A mixture of diene 41 (50 mg, 0.11 mmol) and quinone 33 (21 mg, 0.133 mmol) in toluene (1.5 mL) was heated to 100-110 °C for 24 h. After complete consumption of diene 41, the resulting mixture was concentrated under reduced pressure to give a crude cycloadduct product. The crude cycloadduct product was re-dissolved in CH2Cl2 (10 mL) and m-CPBA (60 mg) was added portion-wise at room temperature, followed by NaHCO₃ (40 mg). The mixture was stirred at room temperature for 24 h, and then Et₃N (0.8 mL) was added at room temperature in an open-air atmosphere and further kept stirring at room temperature for 4 h. After completion of the reaction, the residue was concentrated under reduced pressure and purified by column chromatography (1:4 EtOAc/hexane), affording the aromatized product 42 (38 mg, 45%). Physical appearance: Yellow-orange powder solid; Rf: 0.5 (30% EtOAc/hexane); IR (KBr, cm⁻¹): 3055, 2926, 2857, 2349, 1729, 1673, 1589, 1455, 1381, 13 224, 1265, 1216, 1163, 1094, 1024, 890, 755, 717, 700; $[\alpha]_{D}^{20}$: -26.94 (c = 1.00 CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 8.23 (d, J = 7.4 Hz, 2H), 8.11 (s, 1H), 7.80–7.70 (m, 2H), 7.40-7.30 (m, 10H), 6.08 (d, J = 3.8 Hz, 1H), 5.16-5.11 (m, 1H), 5.02 (d, J = 4.8 Hz, 1H), 4.86–4.81 (m, 1H), 4.77 (d, J = 11.0 Hz, 1H), 4.74 (s, 1H), 4.72 (d, J = 9.6 Hz, 1H), 4.64 (d, J = 13.5 Hz, 1H), 4.57 (d, J = 11.0 Hz, 1H), 4.54 (s, 2H), 1.56 (s, 3H), 1.41 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 183.1, 181.9, 154.9, 145.9, 137.8, 137.1, 135.1, 134.7, 134.4, 133.5, 132.6, 128.7, 128.5, 128.3, 128.0, 128.0, 127.3, 126.8, 126.7, 120.5, 113.0, 105.3, 84.7, 79.4, 73.1, 72.5, 71.3, 70.5, 69.0, 27.1, 26.6. HRMS (ESI-QTOF): $[M + H]^+$ calcd for $C_{37}H_{33}O_8$ 605.2170; found 605.2163.

(8R,8aR,9aR,12aR,12bS)-8-(Benzyloxy)-7-((benzyloxy)methyl)-1-hydroxy-11,11-dimethyl-8a,9a,12a,12b-tetrahydro-8*H*-[1,3]dioxolo [4',5':4,5]furo[3,2-*b*]naphtho[2,3-*h*]chromene-5,14-dione (45). A mixture of diene 41 (50 mg, 0.11 mmol) and dienophile 43 (23 mg, 1.33 mmol) in toluene (1 mL) was heated to 100–110 °C for 20 h. After complete consumption of diene 41,

the resulting mixture was concentrated under reduced pressure to give the crude cycloadduct product 44. The crude cycloadduct product was re-dissolved in CH2Cl2 (10 mL) and m-CPBA (60 mg) followed by NaHCO₃ (40 mg) were added portion-wise at room temperature. The mixture was stirred at room temperature for 24 h, and then Et₃N (0.8 mL) was added at room temperature in an open-air atmosphere and further kept stirring at room temperature for 6 h. After completion of the reaction, the residue was concentrated under reduced pressure and purified by column chromatography (1:5 EtOAc/ hexane), affording the aromatized product 45 (35 mg, 50%). Physical appearance: Yellow sticky solid; Rf: 0.5 (20% EtOAc/ hexane); IR (KBr, cm⁻¹): 3502, 3040, 2926, 2864, 1672, 1638, 1592, 1512, 1454, 1372, 1318, 1262, 1161, 1098, 1023, 890, 836, 756, 699, 670; $[\alpha]_{D}^{20}$: -56. 80 (*c* = 0.65, CHCl₃); ¹H NMR (500 MHz, CDCl₃) δ 12.96 (s, 1H), 8.10 (s, 1H), 7.79–7.73 (m, 1H), 7.61 (t, J = 7.9 Hz, 1H), 7.40-7.27 (m, 11H), 6.09 (d, J = 3.8 Hz, 1H), 5.12 (d, J = 3.8 Hz, 1H), 5.01 (d, J = 4.6 Hz, 1H), 4.85-4.80 (m, 1H), 4.74 (d, J = 11.4 Hz, 2H), 4.69 (d, J = 13.5 Hz, 1H), 4.62 (d, J = 13.5 Hz, 1H), 4.55 (d, J = 11.2 Hz, 1H), 4.53 (s, 2H), 3.81 (s, 1H), 1.56 (s, 3H), 1.42 (s, 3H); ¹³C NMR (125 MHz, CDCl₃) δ 188.2, 182.4, 162.6, 155.4, 146.6, 137.7, 137.0, 136.0, 134.7, 132.8, 128.7, 128.4, 128.3, 128.1, 128.0, 127.2, 124.9, 120.8, 120.0, 119.0, 117.2, 113.2, 105.3, 84.9, 79.8, 77.4, 77.2, 76.9, 73.2, 72.9, 71.4, 70.3, 69.0, 27.2, 26.8; HRMS (ESI-QTOF): $[M + Na]^+$ calcd for $C_{37}H_{32}NaO_9$ 643.1894; found 643.1894.

Data availability

All of the data related to new compounds pertaining to this manuscript are available in the ESI.‡

Conflicts of interest

There are no conflicts to declare.

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