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NHC-Catalyzed Dual Stetter Reaction: A Mild Cascade Annulation for the Syntheses of Naphthoquinones, Isoflavanones, and Sugar-Based Chiral Analogues

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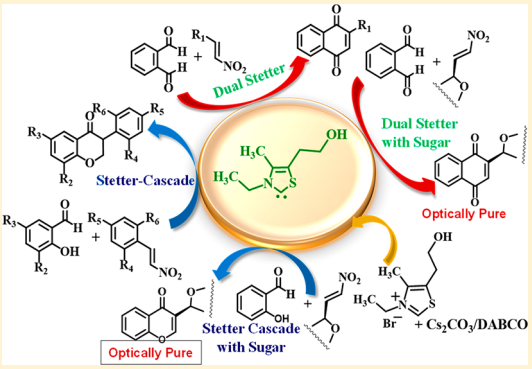
Supporting Information

ABSTRACT: The *N*-heterocycle carbene (NHC)-catalyzed dual Stetter cascade reaction is discovered through coupling of *β*-nitrostyrene with phthalaldehyde under mild conditions to furnish valuable aryl-naphthoquinones. The generality of the new reaction is validated through the development of a C−C and O−C bond forming Stetter cascade reaction using salicylaldehydes to obtain functionalized dihydroisoflavanones. The mild NHC organocatalysis is successfully employed for the construction of optically pure sugar-based naphthoquinones and dihydroisoflavanones. Herein, NHC is found as a unique and powerful organocatalyst to construct homoatomic C−C cross-coupling, heteroatomic O−C bond formation, and cascade cyclization utilizing NO_2 as a leaving group at ambient temperature. A mechanistic pathway of the new metal-free catalysis is predicted on the basis of our ESI-MS study of the ongoing reaction and literature.



INTRODUCTION

The *N*-heterocycle carbenes (NHCs) have gained enormous attention in the last couple of decades because of their remarkable physical, chemical, and selective properties, leading to find diverse applications as outstanding catalysts, useful ligands, radical stabilizers, substrate activators, oxidative and reductive reagents, unpolungs, polymers, liquid crystals, MOFs, photoactive and bioactive materials, and pharmaceuticals.[1] Moreover, organocatalysis of NHCs especially for activation of enal compounds leads to the development of a wide range of new reactions[2] including lactone and lactam formations,[3] cycloadditions,[4] Michael additions,[5] *γ*-amino alkylation of *α,β*-unsaturated esters[6], and self-redox catalysis.[7] Notably, NHCs were frequently employed for fundamental organic transformations such as esterification, transesterification, acylation reaction, 1,2-addition reactions, aza-Morita−Baylis−Hillman reaction, activation of silylated nucleophiles, the transformation of ketenes, cross-coupling, metathesis, and asymmetric processes.[1,8] The organocatalysis reactions were efficiently utilized for the umpolung of aldehydes to generate acyl anion intermediates and developed fundamental transformations such as benzoin condensation and Stetter reaction.[9] The Stetter reactions with *α,β*-unsaturated carbonyls, *α,β*-unsaturated esters, *α,β*-unsaturated nitriles, and *β*-nitrostyrenes were studied to access 1,4-dicarbonyl compounds, 4-ketocarboxylates, nitriles, and nitroalkanes.[9b−d,10,11] Interestingly Cheng[10d] and Hong[12d] et al. in their separate reports described NHC-catalyzed aldehydes-nitrovinyls C−C coupling to produce *β*-nitroketones. NHC-catalyzed cascade reactions employing the umpolung Stetter concept received growing attention among the scientific community because of its utility for easy construction of targeted core structures present in natural products.[12]

A cascade reaction is an attractive synthetic tool, in which more than one bond forming event is performed, avoiding cost-effective and time-consuming protection−deprotection, isolation of intermediates, waste handling, and poor selectivity through coupling of two or more substrates under the same reaction conditions with the same catalyst. The cascade NHC organocatalysis employing the umpolung concept is still limited. Rovis et al. reported a tandem NHC-catalyzed direct synthesis of cyclopentanone derivatives through Michael addition followed by the Stetter reaction under the basic conditions.[2c] Gravel and co-worker established an NHC-catalyzed Stetter−Michael reaction using benzene-1,2-dienyl derivatives and aldehydes to achieve indane diastereomers.[12a] A Stetter−aldol reaction between phthaladehyde and alkene with NHC was performed by Ye and colleagues to furnish the diastereoselective synthesis of 4-hydroxytetralones.[12b] Inspired by the NHC catalysis, we envisioned that a phthaladehyde (**1**) may react with a metal-free NHC to form a "Breslow intermediate", which may couple with a suitable Michael acceptor (**3**), leading to the Stetter adduct (**A**, eq i, Scheme 1). The domino second Stetter cascade (**B**) may trigger off the naphthoquinone derivative (**4**) through a real oxidative

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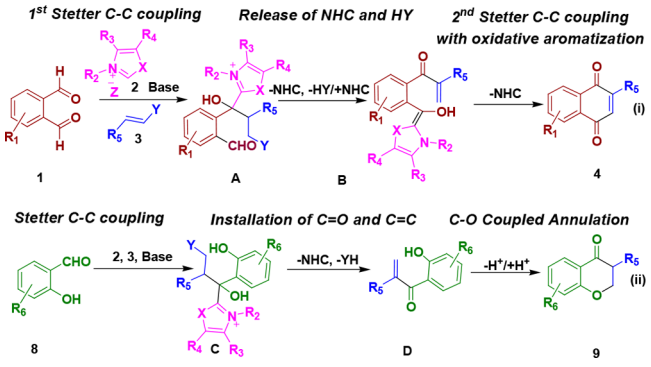
Scheme 1. Proposed Dual Stetter and Stetter Cascade Annulation



aromatization. Interestingly, the development of a mild NHC organocatalysis may furnish biocompatible sugar-based naphthoquinones. Moreover, the reaction path may be verified through replacement of a CHO group (eq (ii) by a nucleophilic OH (**8**), which is expected to pass through the construction of a Stetter intermediate (**C**) along with rapid O−C coupled annulation of **D** to furnish dihydroisoflavanones (**9**).

The naphthoquinones are present in important natural products including all organisms and displayed significant biological activities.[13] For example, phylloquinone 3 [vitamin K_1 (i), Figure 1] and analogues are antimicrobial, anti-

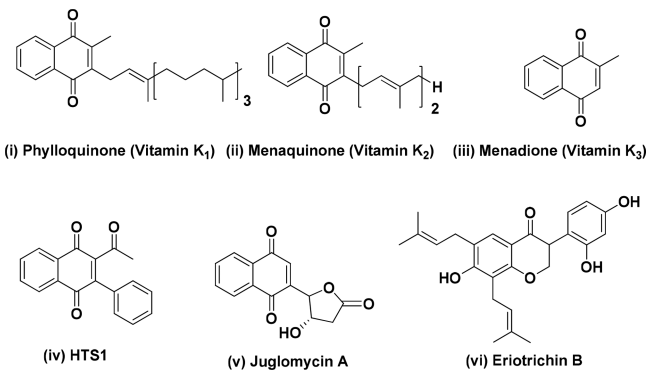


Figure 1. Bioactive naphthoquinones and dihydrosoflavanone.

inflammatory, antimalarial, and cardiotonic agents, and menaquinone 2 [vitamin K_2 (ii)] and menadione 1 [vitamin K_3 (iii)] were employed as synthetic nutritional supplements, blood coagulating agents, and key intermediates to access other group members of vitamin K.[14] Aryl-substituted naphthoquinones exhibit a wide range of medicinal properties.[15] For instance, HST1 (iv) is an anticancer active Hsp90 inhibitor, and the optically active juglomycin A (v) was used as antibacterial pharmaceuticals for both Gram-negative and Gram-positive bacteria.[16] Dihydroisoflavanones are abundant in nature and are found in breast cancer active oblarotenoid C, pterocarpenoids, and eriotrichin B (vi).[17] Indeed the two classes of compounds are drug candidates of choice for current research in medicinal chemistry.[13−17]

Aryl-substituted naphthoquinones were synthesized through the reaction between diazonium salts and boronic acids,[18] Heck arylation of naphthoquinones,[19] oxidative C−H/C−H cross-coupling,[20] using arylboronic acids and $K_2S_2O_8$,[21] IBX and phenylhydrazine,[22] and Ar_2IOTf as aryl radicals.[23] The synthesis of dihydrosoflavanones was mainly performed by Hg^{II}−Pd^{II}-mediated arylation of chromenes, Au^{I}-catalyzed cyclization of salicylaldehydes with aryl acetylenes, and NHC-catalyzed intramolecular hydroacylation of unactivated olefins.[24] However, the reported methods have limitations using environmentally unsafe heavy metal catalysts, expensive starting materials, toxic reagents, and/or harsh reaction conditions, leading to less selectivity and inappropriate synthesis of labile chiral compounds. Thus, the development of a simple, mild, selective, and general organocatalysis strategy is highly desirable to achieve the functionalized carbocycles, heterocycles, and sugar-based chiral analogues.

RESULTS AND DISCUSSION

The dual Stetter reaction was first attempted between readily available *o*-phthalaldehyde (**1**) and a highly electron-deficient Michael acceptor, *β*-nitrostyrene (**3a**, Y = NO_2), in the presence of NHC precursors (**2**) using different bases and solvents at ambient temperature (Table 1). The reaction was unsuccessful using in situ generated NHC from imidazolium chloride (**2a**) or thiazolium iodide (**2b**) in the polar aprotic solvents such as dichloromethane (DCM), dimethylformamide (DMF), acetonitrile (CH_3CN), and tetrahydrofuran (THF) in the presence of organic and inorganic bases (entries 1−9). Upon screening with another inexpensive NHC precursor, thiazolium bromide (**2c**), the dual Stetter reaction was successful (entry 10) to furnish the desired product **4a** with a low yield (32%). However, the reduction of reactivity of **2a** and **2b** due to the exposure to moisture may not be avoided. Gratifyingly, the yield (88%) and reaction rate (9 h) were significantly improved by changing the reaction medium from THF to DCM (entry 11). DABCO and Cs_2CO_3 were found as efficient bases (entries 11 and 12). Bu^tOK and DBU were not effective for the annulation process (entries 13 and 14). We were very much curious to know the role of the departing group (Y) on this cascade reaction. However, the reaction was unsuccessful when using commonly used leaving groups such as OMe, OAc, OTf, OTMS, Cl, or Br (entries 15−20). Herein, a Michael acceptor bearing a strongly electron-deficient Y drives the cascade annulation. From our survey, the best yield (**4a**) was obtained in DCM medium (88%, entries 11 and 12) with respect to DMF (<5%, entry 21), THF (32%, entry 10), and CH_3CN (44%, entry 22). A total of 9 mol % **2c** was sufficient for completion of the reaction (entries 11, 23, and 24) because the reaction time and yield were insignificant. The reaction did not occur in the absence of NHC (entry 25). The inexpensive Cs_2CO_3 is the automatic choice as a base for the dual Stetter reaction (entries 11 and 12).

The scope of the reaction was investigated (Scheme 2) under the mild conditions (entry 11, Table 1) using a wide range of nitroalkenes possessing electron-withdrawing groups at phenyl moieties such as 4-fluoro (entry 2), 4-trifluoromethyl (entry 3), 2-chloro (entry 4), 3-nitro (entry 5), 3,5-dichloronitro (entry 6), and 3,5- (entry 7) to achieve several functionalized naphthoquinones (**4b−g**). The reaction conditions were validated with electron-rich aromatics such as naphthyl and biphenyl nitrostyrene (entries 8 and 9) and also for labile precursors such as furanonitrostyrene, chromenonitrostyrene, and ferrocenenitrostyrene (entries 10−12) to obtain corresponding naphthoquinones with good yields. The electron-poor *β*-nitrostyrenes were usually led to very high yields (81−88%, entries 2−7) by this organocatalyzed cyclization reaction, whereas electron-rich *β*-nitrostyrenes

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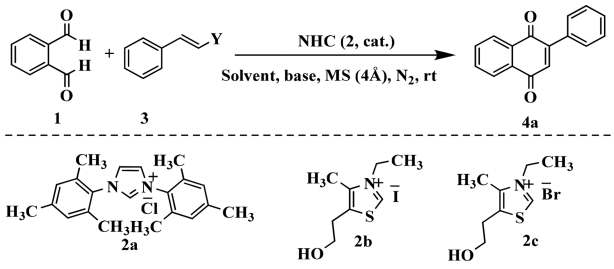
Table 1. Development of Dual Stetter Reaction[a,b]



entry	NHC precursor	Y	base	solvent	time (h)	yield (%)[c]
1	**2a**	NO_2	DBU	DCM	24	nd[d]
2	**2a**	NO_2	DBU	DMF	24	nd
3	**2a**	NO_2	Cs_2CO_3	DCM	24	nd
4	**2b**	NO_2	DBU	DCM	24	nd
5	**2b**	NO_2	Cs_2CO_3	THF	24	nd
6	**2b**	NO_2	Cs_2CO_3	CH_3CN	24	nd
7	**2b**	NO_2	Cs_2CO_3	DCM	24	nd
8	**2b**	NO_2	Bu^tOK	THF	24	nd
9	**2b**	NO_2	Cs_2CO_3	DMF	24	nd
10	**2c**	NO_2	Cs_2CO_3	THF	24	32
11	**2c**	NO_2	Cs_2CO_3	DCM	8	88
12	**2c**	NO_2	DABCO	DCM	10	88
13	**2c**	NO_2	Bu^tOK	DCM	24	nd
14	**2c**	NO_2	DBU	DCM	24	nd
15	**2c**	OMe	Cs_2CO_3	DCM	24	nd
16	**2c**	OAc	Cs_2CO_3	DCM	24	nd
17	**2c**	OTf	Cs_2CO_3	DCM	24	nd
18	**2c**	OTMS	Cs_2CO_3	DCM	24	nd
19	**2c**	Cl	Cs_2CO_3	DCM	12	nd
20	**2c**	Br	Cs_2CO_3	DCM	24	nd
21	**2c**	NO_2	Cs_2CO_3	DMF	12	<5
22	**2c**	NO_2	Cs_2CO_3	CH_3CN	11	44
23	**2c**[e]	NO_2	Cs_2CO_3	DCM	10	88
24	**2c**[f]	NO_2	Cs_2CO_3	DCM	18	83
25[g]		NO_2	Cs_2CO_3	DCM	24	nd

[a]Reaction conditions: phthalaldehyde (**1a**, 1.0 mmol), *β*-nitrostyrene (**3a**, 1.5 mmol), solvent (5 mL), NHC precursor **2a–c** (10 mol %), base (20 mol %), stirred at ambient temperature. [b]MS: Molecular sieves. [c]Yield of the product obtained after purification by silica gel column chromatography. [d]nd: **4a** not detected. [e]**2c**: 9 mol %. [f]**2c**: 8 mol %. [g]Without NHC.

furnished the desired products (**4m**, **4o**) in moderate yields (51–55%, entries 13 and 15). Substituted phthalaldehyde (**1b**, entry 14) was smoothly transformed into the desired product **4n**. To understand the reactivity, selectivity, and versatility of the NHC catalysis, we employed more sterically hindered nitrostyrenes (**3o–r**, entries 16–19), bearing unsubstituted and 4-Me-, 4-OMe-, as well as 4-Cl-substituted phenyl residues. Interestingly, all olefins selectively transformed into the desired 2,3-disubstituted naphthoquinones (**4p–s**) in excellent yields (78–85%) under the mild reaction conditions. Herein, the NO_2 group plays two important roles such as making olefins susceptible to react with the NHC-aldehyde adduct and complete the cascade cyclization through its elimination.

Apart from probing the viability of the designed strategy, our main objective was to develop a metal-free mild strategy for synthesizing potential biocompatible optically pure compounds bearing labile sugar-based moieties. With this intention, first, sugar-based protected pentose (**5a–c**, Scheme 3) and triose (**5d**) aldehydes were synthesized from D-glucose and D-mannitol, respectively.[25] Nitroalkenes (**6a–d**) were prepared by nitro-aldol and followed by dehydration reaction in the presence of NaOH. To our delight, (+)-2-((3a*R*,5*R*,6*S*,6a*R*)-6-(benzyloxy)-2,2-dimethyltetrahydrofuro[2,3-*d*][1,3]dioxol-5-yl)naphthalene-1,4-dione (**7a**) was obtained in good yield (62%) on treatment of chiral nitroolefin (**6a**) with phthalaldehyde (**1**) for 12 h (entry 1, Scheme 4) under the developed reaction conditions (entry 11, Table 1). Other two pentose-based nitroalkenes (**6b**, **6c**, entries 2 and 3, Scheme 4) also provided corresponding chiral centers-decorated naphthoquinones (**7b**, **7c**) with comparable yield (entries 2, 3). The mild NHC-organocatalysis process was smoothly constructed the desired compound even with the smallest sugar derivative (**6d**) to furnish **7d** (entry 4) in good yield (64%).

To understand the chemo- and regioselectivity and mechanistic pathway of the new NHC organocatalysis, we investigated the possible C–C/O–C coupled Stetter cascade cyclization involving C3 to produce the fully aromatic byproduct chromone under mild conditions. A wide range of pharmaceuticals, agrochemicals, and other applications of functionalized dihydroisoflavanones led us to expand the new strategy for synthesizing the heterocycle. Compounds **9b–k** were synthesized in moderate to high yields (60–82%) within 10–18 h at ambient temperature. Several substituents such as electron-donating Me and OMe (**8f,g**, **3c**, entries 9–11), and electron-withdrawing Cl, Br, dichloro and chloro, bromo (**8b–e**, **3b**, entries 2–8) in salicylaldehydes (**8**), and *β*-nitrostyrenes (**3**) were well-tolerated under the mild conditions. Herein, NHC (**2c**) is found as a unique organocatalyst to display homoatomic (C–C) cross-coupling along OH and CHO of salicylaldehyde (**8a**) with *β*-nitrostyrene (**3a**) to access 3-phenyl dihydroisoflavanone, i.e., chromanone (**9a**, entry 1, Scheme 4) and/or its aromatized isoflavone, i.e., chromone. Unfortunately, the cyclization reaction was unsuccessful under the developed conditions (entry 11, Table 1). Upon screening with different bases, DABCO (20 mol %) was found as the most efficient base for precursor **8a**, bearing acidic functionality (OH, Scheme 5). The formation of **9a** is very much significant to our proposed dual Stetter cascade reaction (Scheme 1). It is expected the first Stetter C–C coupling (**C**, eq (ii) the NHC-catalysis undergoes O–C coupled cascade cyclization through transnitration to furnish dihydroisoflavanone derivative (**9a**). However, a possibility of a Stetter–Michael NHC cascade reaction may not be avoided. Moreover, it nicely addresses the chemo- and regioselectivity during dual coupling processes and even did not install a double bond between C2 and with a heteroatomic (O–C) bond forming cascade cyclization, utilizing NO_2 as a leaving group under mild conditions.

The development of this mild method was useful to synthesize sugar-based chiral dihydroisoflavanones (**10**, Scheme 5). (+)-(3a*R*,5*R*,6*S*,6a*R*)-6-(Benzyloxy)-2,2-dimethyl-5-((*E*)-2-nitrovinyl)tetrahydrofuro[2,3-*d*][1,3]dioxole (**6a**) and its methyl analogue (**6b**) transformed into the desired chirally modified dihydroisoflavanones (entries 1 and 2; **10a** and **10b**) through NHC-catalyzed C–C/O–C coupled annulation of salicylaldehydes (**8a** and **8b**). It is noteworthy that salicylaldehydes possessing an acidic OH group were not harmful to acid-sensitive protected sugar substrates during the NHC-catalyzed cyclization process under the developed reaction conditions. It is expected that the potential

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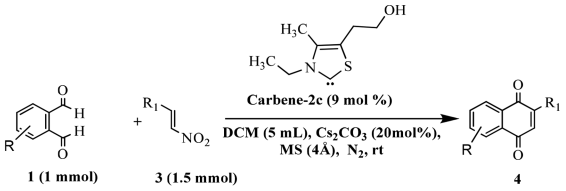
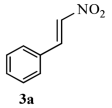
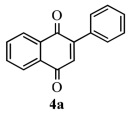
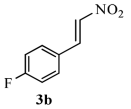
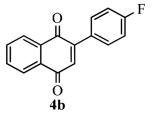
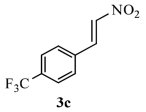
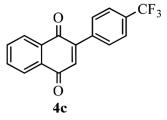
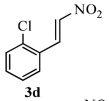
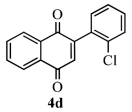
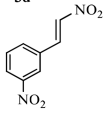
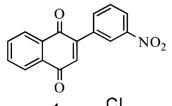
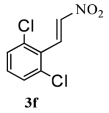
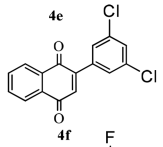
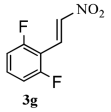
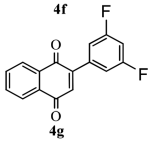
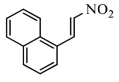
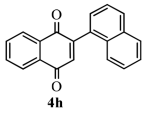
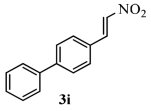
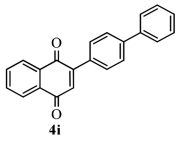
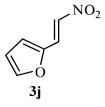
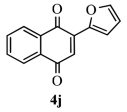
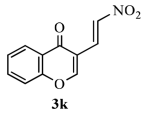
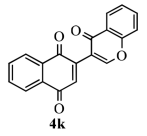
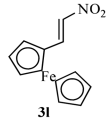
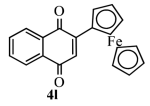
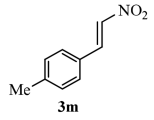
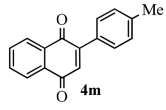
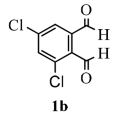
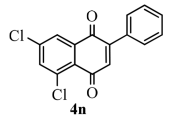
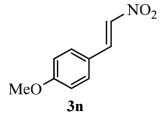
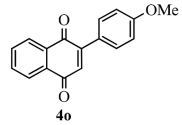
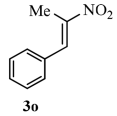
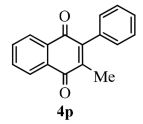
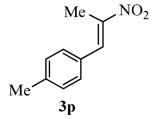
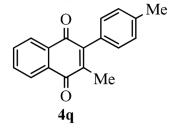
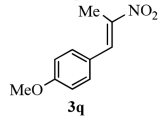
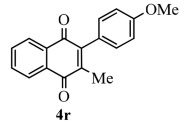
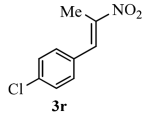
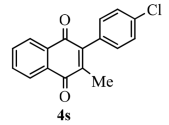
Scheme 2. Synthesized Data of Arylnaphthoquinones



Entry	Phthalaldehyde	Olefin (3)	Time (h)	Naphthouinone (4)	Yield (%)
1	 1a	 3a	8	 4a	88
2	1a	 3b	9	 4b	86
3	1a	 3c	8	 4c	81
4	1a	 3d	9	 4d	82
5	1a	 3e	8	 4e	88
6	1a	 3f	9	 4f	86
7	1a	 3g	9	 4g	84
8	1a	 3h	10	 4h	80
9	1a	 3i	10	 4i	76
10	1a	 3j	12	 4j	72

Entry	Phthalaldehyde	Olefin (3)	Time (h)	Naphthouinone (4)	Yield (%)
11	1a	 3k	12	 4k	62
12	1a	 3l	12	 4l	66
13	1a	 3m	14	 4m	54
14	 1b	3a	15	 4n	52
15	1a	 3n	17	 4o	50
16	1a	 3o	12	 4p	80
17	1a	 3p	14	 4q	78
18	1a	 3q	10	 4r	82
19	1a	 3r	12	 4s	85

biocompatible new sugar-based optically pure carbocycles (**7**, Scheme 3) and heterocycles (**10**, Scheme 5) will find applications in the modern biology for developing useful pharmaceuticals.

The exact mechanism of the new organocatalysis is unknown to us. However, a plausible mechanism is predicted (Scheme 6) on the basis of reported literature[9,26] and our ESI-MS study of the ongoing dual Stetter and Stetter cascade reactions. "Breslow intermediate" I may be formed through coupling of **1a** and NHC (**2c**), which is expected to react with **3a**, leading to the formation of Stetter intermediate II. Upon release of NHC, followed by elimination of HNO_2, the corresponding enone (III) may be obtained (path A, when X = CHO, Z = H). Another Breslow intermediate (IV) is expected to form in the second Stetter reaction through coupling of the remaining aldehyde functionality with NHC, which may undergo intramolecular C−C coupling to generate a putative intermediate V. The release of NHC from V, followed by aromatization, led to the formation of **4a**. Similarly for the synthesis of dihydroisoflavanones, Stetter intermediate II (path B, when X = OH; Z = Cl), which may be generated from **8b**, was expected to form enone intermediate VI through the

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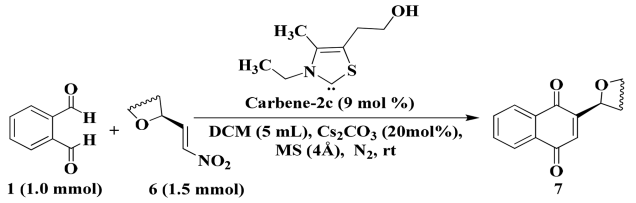
Scheme 3. Asymmetric Synthesis of Sugar-Based Naphthoquinones



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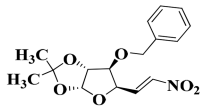
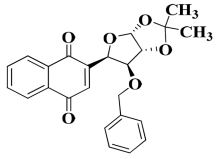
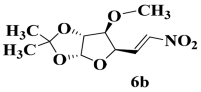
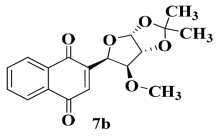
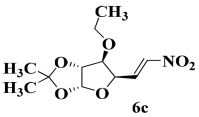
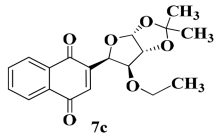
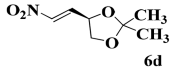
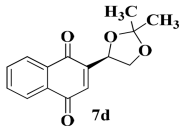
1	 6a	12	 7a	62
2	 6b	12	 7b	58
3	 6c	12	 7c	56
4	 6d	12	 7d	64

release of NHC and HNO_2. Finally, intramolecular oxa-Michael addition will trigger **9b**. From our ESI-MS reaction kinetics of the ongoing reaction among **1a**, **3a**, and **2c**, symbolic ESI-MS peaks were detected for Breslow intermediate I (or **2c**−**1a** adduct) at *m*/*z* 306.1339 (path a), intermediate II at *m*/*z* 455.1755, and **4a** at *m*/*z* 235.0980. Similarly, the symbolic ESI-MS peaks were observed for the Stetter cascade annulation among **8b**, **3a**, and **2c** such as Breslow intermediate (bearing Cl) I (or **2c**−**8b** adduct) at *m*/*z* 328.0855 and 330.0882 and **9b** at *m*/*z* 259.0528 and 261.0398. These findings support the proposed catalytic cycles.

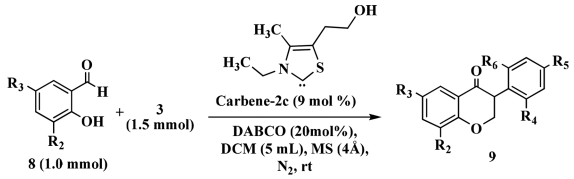
CONCLUSIONS

In conclusion, the discovery of the NHC-catalyzed dual Stetter and Stetter cascade cyclization reactions under mild conditions to furnish functionalized naphthoquinones, biologically potent sugar-based naphthoquinones and dihydroisoflavanones, studies on the reaction mechanism, operational simplicity, and development of a general method will find considerable applications in synthetic chemistry and its allied branches.

EXPERIMENTAL SECTION

General Information. The chemicals and solvents were procured from commercial vendors and utilized without further purification unless otherwise mentioned. The solvents, ethyl acetate and petroleum ether, were purified by a distillation technique. DCM was dried through distillation using P_2O_5 prior to use. The petroleum ether used in our experiments had a boiling range from 60 to 80 °C. Column chromatography was done using silica gel (60−120 mesh, 0.12−0.25 mm) as a stationary phase. Analytical thin-layer chromatography was performed on 0.25 mm extra-hard silica gel plates with the UV254 fluorescent indicator. The reported melting points are uncorrected. ^{1}H NMR and ^{13}C NMR spectra were recorded at ambient temperature using 300 MHz spectrometers (300 MHz for ^{1}H and 75 MHz for ^{13}C). Chemical shift values of the compounds are reported in ppm with respect to tetramethylsilane as the internal reference, and coupling constants (*J*) are reported in hertz (Hz). The ^{1}H NMR peak multiplicities were presented in standard

Scheme 4. Stetter Cascade Cyclization to Dihydroisoflavanones



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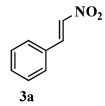
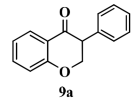
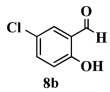
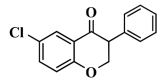
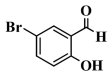
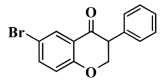
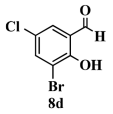
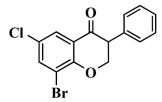
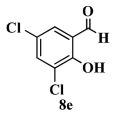
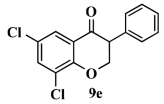
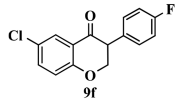
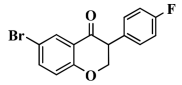
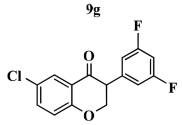
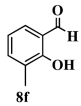
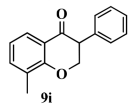
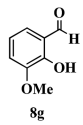
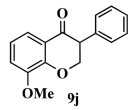
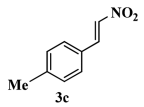
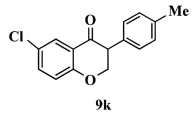
1	 8a	 3a	10	 9a	72
2	 8b	3a	12	 9b	82
3	 8c	3a	12	 9c	78
4	 8d	3a	12	 9d	74
5	 8e	3a	12	 9e	76
6	8b	3b	10	 9f	67
7	8c	3b	12	 9g	71
8	8b	3g	10	 9h	75
9	 8f	3a	16	 9i	66
10	 8g	3a	16	 9j	60
11	8b	 3c	18	 9k	64

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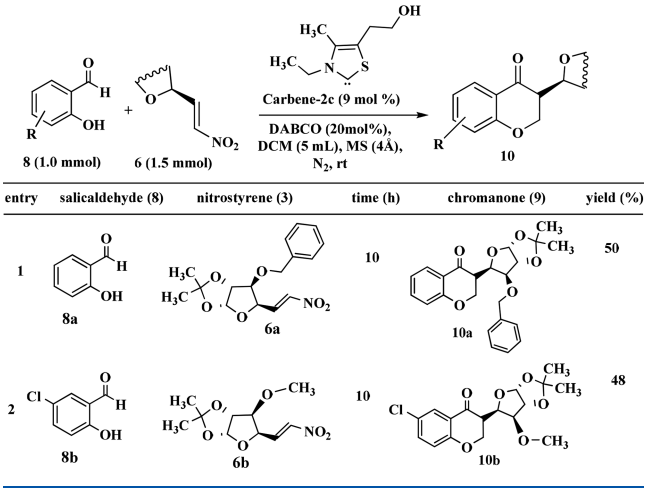
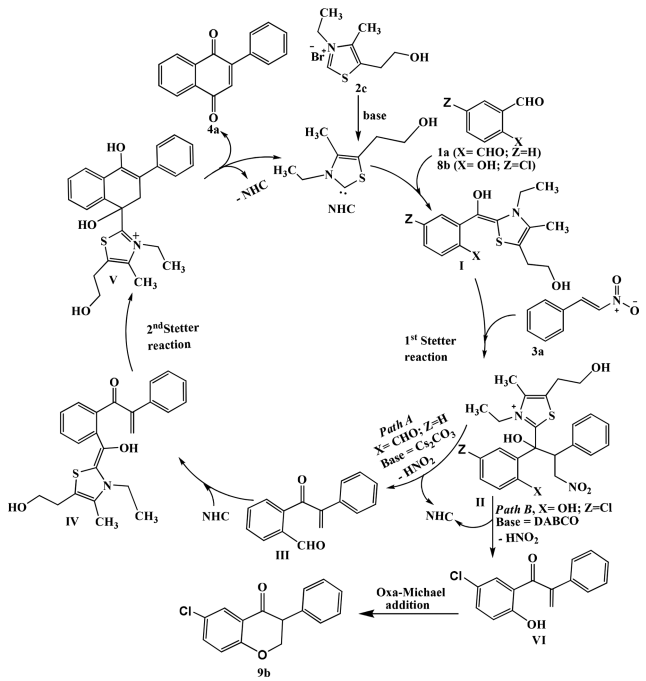
Scheme 5. Asymmetric Synthesis of Sugar-Based Dihydroisoflavanones



Scheme 6. Plausible Mechanism of Dual Stetter and Stetter Cascade



format such as s (singlet), d (doublet), dd (double doublet), t (triplet), q (quartet), and m (multiplet). Infrared spectra were measured on an IR spectrometer using thin films. The optical rotation of the chiral compounds was recorded in a polarimeter. HRMS data were recorded on a Q-tof-micro quadruple mass spectrophotometer.

General Procedure for the Synthesis of Nitroolefins (3a–l and 6a–d).[27] To a stirred mixture solution of aldehyde derivative (10 mmol) and nitromethane (10 mmol) in methanol (5 mL) at 0 °C was added an aqueous solution of sodium hydroxide (15 mmol) over a period of 30 min. The stirring was continued for another half an hour in the temperature range from 0 to 5 °C. The mixture was allowed to warm to room temperature. Completion of the reaction was confirmed through monitoring by TLC (10–12 h). The post reaction mixture was mixed with water (20 mL) and poured over crushed ice containing concentrated HCl (2 mL). The yellow precipitate was filtered, dried in a vacuum desiccator, and crystallized from hot EtOH. The desired nitroolefins were obtained in 90–95% yields. Similarly, other nitroolefins were also synthesized.

General Procedure for the Synthesis of Naphthoquinones (4a–l). Phthalaldehyde **1a** (1.0 mmol) and nitroolefine **3** (1.5 mmol) were added in dry DCM (5 mL) in the presence of thiazolium bromide **2c** (9 mol %) and activated 4 Å MS (300 mg) in the inert condition under a nitrogen atmosphere, and the mixture was stirred for 30 min. Cs_2CO_3 (20 mol %) was added to the reaction mixture, and the mixture was stirred at ambient temperature until the reaction was completed. The progress of the reaction was monitored through TLC. The post reaction mixture was filtered through a Celite bed, and the filtrate was extracted with EtOAc (2 × 15 mL). The organic part was washed with water (3 × 10 mL) and brine (1 × 10 mL). It was dried over anhydrous Na_2SO_4, filtered, and evaporated in a rotary evaporator under reduced pressure at room temperature. The product was purified by utilizing silica gel (60–120 mesh) column chromatography with ethyl acetate–petroleum ether (10–30%, v/v) as an eluent, which afforded the corresponding naphthoquinones.

*2-Phenylnaphthalene-1,4-dione (**4a**).* Compound **4a** was prepared using *β*-nitrostyrene (**3a**) as a starting material to give the product as a yellow solid: 88% yield (206 mg); mp 108–110 °C (lit.[28] 110–112 °C); ^{1}H NMR (300 MHz, $CDCl_3$) *δ* 7.01 (s, 1H), 7.01–7.43 (m, 3H), 7.49–7.52 (m, 2H), 7.69–7.73 (m, 2H), 8.04–8.12 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 126.0, 127.1, 128.5, 129.4, 130.0, 132.2, 133.4, 133.8, 133.9, 135.2, 148.4, 185.1, 184.1; FTIR (KBr, cm^{-1}) 3068, 2962, 1666, 1592, 1306, 1248, 1206, 792, 576; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{11}O_2$ $[M + H]^+$ 235.0759, found 235.0780.

*2-(4-Fluorophenyl)naphthalene-1,4-dione (**4b**).* Compound **4b** was prepared using 4-fluoro-*β*-nitrostyrene (**3b**) as a starting material to give the product as a yellow solid: 86% yield (217 mg); mp 140–142 °C (lit.[29] 142–144 °C); ^{1}H NMR (300 MHz, $CDCl_3$) *δ* 6.97 (s, 1H), 7.06–7.11 (m, 2H), 7.49–7.52 (m, 2H), 7.68–7.72 (m, 2H), 8.02–8.12 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 115.4, 115.7, 125.9, 127.1, 129.3, 131.3, 131.4, 132.0, 132.3, 133.8, 134.9, 146.9, 163.5, 166.8, 184.3, 184.9; FTIR (KBr, cm^{-1}) 3062, 2960, 1740, 1682, 1593, 1502, 1301, 1260, 1160, 1102, 1007; HRMS (ESI) *m*/*z* calcd for$C_{16}H_{10}FO_2$ $[M + H]^+$ 253.0665, found 253.0663.

*2-(4-(Trifluoromethyl)phenyl)naphthalene-1,4-dione (**4c**).*[30] Compound **4c** was prepared using 4-trifluoromethyl-*β*-nitrostyrene (**3c**) as a starting material to give the product as a yellow solid: 81% yield (245 mg); mp 122–124 °C; ^{1}H NMR (300 MHz, $CDCl_3$) *δ* 7.05 (s, 1H), 7.61–7.77 (m, 6H), 8.07–8.16 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 125.4, 125.2, 127.1, 129.7, 130.2, 131.3, 131.4, 132.0, 132.3, 133.8, 134.9, 136.1, 137.1, 148.5, 183.9, 184.8; FTIR (KBr, cm^{-1}) 3068, 2962, 1666, 1592, 1306, 1248, 1206, 792, 576; FTIR (KBr, cm^{-1}) 3075, 2922, 1668, 1582, 1326, 1262, 1178, 1106, 742, 706; HRMS (ESI) *m*/*z* calcd for $C_{17}H_{10}F_3O_2$ $[M + H]^+$ 303.0633, found 303.0635.

*2-(2-Chlorophenyl)naphthalene-1,4-dione (**4d**).* Compound **4d** was prepared using 2-chloro-*β*-nitrostyrene (**3d**) as a starting material to give the product as a yellow solid: 82% yield (220 mg); mp 132–134 °C; ^{1}H NMR (300 MHz, $CDCl_3$) *δ* 6.90 (s, 1H), 7.16–7.41 (m, 4H), 7.68–7.71 (m, 2H), 8.03–8.08 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 126.2, 126.7, 127.1, 129.7, 130.6, 132.0, 132.1, 133.1, 133.8, 134.0, 137.3, 148.2, 183.0, 184.8; FTIR (KBr, cm^{-1}) 3072, 2915, 1666, 1592, 1362, 1310, 1252, 1166, 1092, 1055, 772, 577; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{10}ClO_2[M + H]^+$ 269.0369, found 269.0367 (one of the major peaks).

*2-(3-Nitrophenyl)naphthalene-1,4-dione (**4e**).* Compound **4e** was prepared using 3-nitro-*β*-nitrostyrene (**3e**) as a starting material to give the product as a yellow solid: 88% yield (246 mg); mp 130–132 °C; ^{1}H NMR (300 MHz, $CDCl_3$) *δ* 7.19 (s, 1H), 7.59–7.70 (m, 3H), 7.93 (d, *J* = 7.5 Hz, 1H), 8.27–8.47 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 122.2, 125.5, 127.0, 127.1, 127.1, 127.3, 127.4, 128.5, 129.9, 130.0, 132.8, 137.5, 144.3, 148.1, 183.9, 184.9; FTIR (KBr, cm^{-1}) 3082, 2915, 1662, 1590, 1366, 1310, 1262, 1126; HRMS (ESI) *m*/*z* calcd for $C_{16}H_{10}NO_4$ $[M + H]^+$ 280.0610, found 280.0612.

*2-(2,6-Dichlorophenyl)naphthalene-1,4-dione (**4f**).* Compound **4f** was prepared using 2,6-dichloro-*β*-nitrostyrene (**3f**) as a starting material to give the product as a yellow solid: 86% yield (221 mg); mp 205–206 °C; ^{1}H NMR (300 MHz, $CDCl_3$) *δ* 6.95 (s, 1H), 7.23–

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7.41 (m, 3H), 7.77−7.79 (m, 2H), 8.13−8.15 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 126.3, 127.1, 127.9, 130.6, 131.9, 132.1, 132.2, 134.0, 134.0, 134.2, 138.7, 146.1, 182.2, 184.5; FTIR (KBr, cm^{-1}) 3092, 2910, 1665, 1588, 1462, 775, 612; HRMS (ESI) m/z calcd for $C_{16}H_9Cl_2O_2$ $[M + H]^+$ 302.9980, found 302.9982 (one of the major peaks).

*2-(2,6-Difluorophenyl)naphthalene-1,4-dione (**4g**).* Compound **4g** was prepared using 3,5-difluoro-β-nitrostyrene (**3g**) as a starting material to give the product as a yellow solid: 84% yield (227 mg); mp 194−196 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.04−7.15 (m, 3H), 7.42−7.50 (m, 1H), 7.83−7.86 (m, 2H), 8.18−8.24 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 111.0, 111.2, 111.4, 111.5, 111.6, 111.7, 126.3, 127.1, 131.4, 131.5, 131.9, 132.0, 134.0 (d, J = 18.0 Hz), 139.5 (d, J = 21.0 Hz), 158.5 (d, J = 27.0 Hz), 161.8 (d, J = 27.0 Hz), 182.1, 184.3; FTIR (KBr, cm^{-1}) 3072, 2912, 1667, 1582, 1463, 1162, 1010; HRMS (ESI) m/z calcd for $C_{16}H_9F_2O_2$ $[M + H]^+$ 271.0571, found 271.0572.

*1,2′-Binaphthyl-1′,4′-dione (**4h**).* Compound **4h** was prepared using (*E*)-1-(2-nitrovinyl)naphthalene (**3h**) as a starting material to give the product as a yellow solid: 80% yield (227 mg); mp 184−186 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.02 (s, 1H), 7.14−7.46 (m, 4H), 7.56 (d, J = 8.1 Hz, 1H), 7.67−7.86 (m, 4H), 8.06−8.08 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 125.0, 125.3, 126.1, 126.1, 126.5, 127.1, 127.3, 128.5, 129.8, 131.3, 131.7, 132.2, 132.3, 133.4, 133.9, 133.9, 137.8, 149.5, 184.3, 185.0; FTIR (KBr, cm^{-1}) 3066, 2922, 2832, 2726, 1671, 1526, 1452, 1412; HRMS (ESI) m/z; $[M + H]^+$ calcd for $C_{20}H_{13}O_2$ 285.0916, found 285.0918.

*2-(Biphenyl-4-yl)naphthalene-1,4-dione (**4i**).* Compound **4i** was prepared using (*E*)-4-(2-nitrovinyl)biphenyl (**3i**) as a starting material to give the product as a yellow solid: 76% yield (236 mg); mp 174−176 °C (lit.[31] 174−175 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.07 (s, 1H), 7.19 (s, 1H), 7.32−7.43 (m, 3H), 7.57−7.74 (m, 7H), 7.89 (d, J = 8.1 Hz, 1H), 8.05−8.16 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 125.9, 127.0, 127.1, 127.3, 127.6, 127.8, 128.9, 129.9, 130.2, 132.2, 132.5, 133.8, 134.8, 140.1, 142.9, 147.7, 184.5, 185.1; FTIR (KBr, cm^{-1}) 3060, 2926, 2833, 2728, 1662, 1528, 1456, 1422; HRMS (ESI) m/z calcd for $C_{22}H_{15}O_2$ $[M + H]^+$ 311.1072, found 311.1073.

*2-(Furan-2-yl)naphthalene-1,4-dione (**4j**).* Compound **4j** was prepared using (*E*)-2-(2-nitrovinyl)furan (**3j**) as a starting material to give the product as a yellow solid: 72% yield (161 mg); mp 176−178 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.23−7.27 (m, 2H), 7.51−7.62 (m, 2H), 7.77−7.82 (m, 2H), 7.98−8.01 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 110.3, 113.3, 127.1, 129.4, 131.1, 132.7, 133.7, 134.3, 146.5, 146.8, 150.1, 183.0, 184.8; FTIR (KBr, cm^{-1}) 3062, 2926, 2832, 1660, 1595, 1462; HRMS (ESI) m/z calcd for $C_{14}H_9O_3$ $[M + H]^+$ 225.0552, found 225.0555.

*2-(4-Oxo-4H-chromen-3-yl)naphthalene-1,4-dione (**4k**).* Compound **4k** was prepared using (*E*)-3-(2-nitrovinyl)-4*H*-chromen-4-one (**3k**) as a starting material to give the product as a yellow solid: 62% yield (187 mg); mp 262−264 °C (lit.[32] 266−268 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.41−7.62 (m, 4H), 7.80−7.83 (m, 3H), 7.98−8.01 (m, 2H), 8.31 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 118.4, 119.2, 125.2, 125.8, 126.1, 130.7, 132.2, 133.5, 134.3, 136.0, 137.0, 139.2, 143.4, 145.4, 162.4, 179.4, 183.2, 185.5; FTIR (KBr, cm^{-1}) 3032, 2925, 2830, 1672, 1662, 1582, 1472, 1252; HRMS (ESI) m/z calcd for $C_{19}H_{11}O_4$$[M + H]^+$ 303.0657, found 303.0658.

*2-(Ferrocene-yl)naphthalene-1,4-dione (**4l**).* Compound **4l** was prepared using (*E*)-2-(2-nitrovinyl)ferrocene (**4l**) as a starting material to give the product as a yellow thick liquid: 86% yield (221 mg); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.15−4.27 (m, 6H), 4.53−4.61 (m, 4H), 7.19 (s, 2H), 7.77−7.80 (m, 2H), 8.05−8.09 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 69.1, 69.3, 69.7, 72.4, 73.0, 130.0, 132.1, 135.6, 136.4, 137.0, 137.2, 138.8, 148.7, 184.0, 186.8; FTIR (neat, cm^{-1}) 3082, 2915, 2826, 1672, 1666, 1566, 1412, 1262, 1138, 706; HRMS (ESI) m/z calcd for $C_{20}H_{15}FeO_2$ $[M + H]^+$ 343.0421, found 343.0422.

*2-p-Tolylnaphthalene-1,4-dione (**4m**).* Compound **4m** was prepared using (*E*)-1-methyl-4-(2-nitrovinyl)benzene (**3m**) as a starting material to give the product as an orange solid: 54% yield (135 mg); mp 100−101 °C (lit.[23] 103−104 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.28 (s, 3H), 6.95 (s, 1H), 7.10 (d, J = 7.8 Hz, 2H), 7.39 (d, J = 8.1 Hz, 2H), 7.55−7.65 (m, 3H), 7.84 (d, J = 7.5 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.4, 123.6, 125.4, 127.5, 127.9, 129.4, 130.9, 134.3, 141.1, 143.5, 152.6, 184.4, 185.2; HRMS (ESI) m/z calcd for $C_{17}H_{13}O_2$ $[M + H]^+$ 249.0916, found 249.0913.

*5,7-Dichloro-2-phenylnaphthalene-1,4-dione (**4n**).* Compound **4n** was prepared using 3,5-dichlorophthalaldehyde (**1b**) as a starting material to give the product as a thick liquid: 52% yield (156 mg); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.00 (s, 1H), 7.48−7.66 (m, 4H), 7.74 (d, J = 1.8 Hz, 2H), 7.87−7.90 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 127.6, 128.3, 128.8, 129.6, 130.0, 133.5, 133.9, 134.3, 136.0, 136.3, 138.4, 142.4, 148.5, 184.7, 185.8; FTIR (KBr, cm^{-1}) 3085, 2969, 1656, 1582, 1326, 1258, 1204, 722, 556; HRMS (ESI) m/z calcd for $C_{16}H_9Cl_2O_2$ $[M + H]^+$ 302.9980, found 302.9984 (one of the major peaks).

*2-(4-Methoxyphenyl)naphthalene-1,4-dione (**4o**).* Compound **4o** was prepared using (*E*)-1-methoxy-4-(2-nitrovinyl)benzene (**3n**) as a starting material to give the product as a yellow solid: 50% yield (130 mg); mp 130−132 °C (lit.[23] 132−133 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.81 (s, 3H), 6.92 (d, J = 8.7 Hz, 2H), 7.12 (s, 1H), 7.69−7.76 (m, 4H), 7.88−7.90 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.3, 114.0, 129.5, 130.7, 131.6, 133.5, 136.0, 139.8, 149.9, 164.3, 182.9, 184.6; HRMS (ESI) m/z calcd for $C_{17}H_{13}O_3$ $[M + H]^+$ 265.0865, found 265.0863.

General Procedure for the Synthesis of Sugar-Based Naphthoquinones (7a−d). Phthalaldehyde (**1a**, 1.0 mmol) and sugar nitroolefin (**7**, 1.5 mmol) were added in dry DCM (5 mL) in the presence of thiazolium bromide **2c** (9 mol %) and activated 4 Å MS (300 mg) under an inert nitrogen atmosphere, and the mixture was stirred for 30 min. Cs_2CO_3 (20 mol %) was added to the reaction mixture, and it was stirred at ambient temperature until the reaction was completed. The progress of the reaction was checked by TLC. The post reaction mixture was filtered through a Celite bed, and the filtrate was extracted with EtOAc (2 × 15 mL). The combined organic portion was washed with water (3 × 10 mL) and brine (1 × 10 mL), dried over activated Na_2SO_4, filtered, and evaporated to dryness in a rotary evaporator at ambient temperature. The crude product was chromatographed on silica gel (60−120 mesh) with ethyl acetate−petroleum ether (10−30%, v/v) as an eluent, which afforded the corresponding naphthoquinones.

*2-((3aR,5R,6S,6aR)-6-(Benzyloxy)-2,2-dimethyltetrahydrofuro-[2,3-d][1,3]dioxol-5-yl)naphthalene-1,4-dione (**7a**).* Compound **7a** was prepared using (3a*R*,5*R*,6*S*,6a*R*)-6-(benzyloxy)-2,2-dimethyl-5-((*E*)-2-nitrovinyl)tetrahydrofuro[2,3-*d*][1,3]dioxole (**6a**) as a starting material to give the product as a yellow semisolid: 62% yield (252 mg); $[\alpha]_D^{25}$ +12.6 (*c* 0.30, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.16 (s, 3H), 1.35 (s, 3H), 3.45−3.62 (m, 1H), 3.91−4.02 (m, 3H), 4.36 (d, J = 3.9 Hz, 1H), 5.77 (d, J = 3.9 Hz, 1H), 6.97 (s, 1H), 7.21−7.32 (m, 5H), 7.87−7.91 (m, 2H), 8.05−8.08 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 29.3, 29.6, 72.8, 79.1, 83.5, 84.3, 111.6, 1222.6, 126.1, 127.1, 127.1, 128.3, 129.8, 130.6, 131.1, 132.5, 134.5, 134.9, 136.2, 138.4, 148.1, 186.0, 188.8; 126.0, 127.1, 128.5, 129.4, 130.0, 132.2, 133.4, 133.8, 133.9, 135.2, 148.4, 185.1, 184.1; FTIR (neat, cm^{-1}) 3072, 2968, 2852, 1676, 1562, 1422, 1350, 1288, 1206, 1150; HRMS (ESI) m/z calcd for $C_{24}H_{23}O_6$ $[M + H]^+$ 407.1495, found 407.1496.

*2-((3aR,5R,6S,6aR)-6-Methoxy-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-5-yl)naphthalene-1,4-dione (**7b**).* Compound **7b** was prepared using (3a*R*,5*R*,6*S*,6a*R*)-6-methoxy-2,2-dimethyl-5-((*E*)-2-nitrovinyl)tetrahydrofuro[2,3-*d*][1,3]dioxole (**6b**) as a starting material to give the product as a yellow thick liquid: 58% yield (191 mg); $[\alpha]_D^{25}$ −19.6 (*c* 0.30, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.22 (s, 3H), 1.39 (s, 3H), 3.31 (s, 3H), 3.41−3.66 (m, 1H), 4.02−4.06 (m, 1H), 4.53 (d, J = 3.9 Hz, 1H), 5.84 (d, J = 3.9 Hz, 1H), 6.98 (s, 1H), 7.68−7.72 (m, 2H), 8.07−8.10 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.9, 26.4, 57.7, 79.5, 81.2, 83.8, 111.1, 122.7, 127.5, 130.7, 132.2, 133.4, 134.2, 135.3, 136.5, 146.6, 186.9, 187.5; FTIR (neat, cm^{-1}) 3042, 2936, 2834, 1672, 1568, 1423, 1352, 1289, 1208, 1155; HRMS (ESI) m/z calcd for $C_{18}H_{19}O_6$ $[M + H]^+$ 331.1182, found 331.1184.

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*2-((3aR,5R,6S,6aR)-6-Ethoxy-2,2-dimethyltetrahydrofuro[2,3-d]-[1,3]dioxol-5-yl)naphthalene-1,4-dione (**7c**).* Compound **7c** was prepared using (3a*R*,5*R*,6*S*,6a*R*)-6-ethoxy-2,2-dimethyl-5-((*E*)-2-nitrovinyl)tetrahydrofuro[2,3-*d*][1,3]dioxole (**6c**) as a starting material to give the product as a yellow thick liquid: 56% yield (193 mg); $[\alpha]_D^{25}$ −22.8 (*c* 0.30, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.09−1.17 (m, 5H), 1.39 (s, 3H), 3.91−3.99 (m, 1H), 4.05−4.12 (m, 1H), 4.54−4.66 (m, 3H), 5.86 (d, *J* = 3.1 Hz, 1H), 6.98 (s, 1H), 7.68−7.72 (m, 2H), 8.07−8.10 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 15.8, 25.9, 26.4, 66.5, 79.5, 81.2, 83.8, 111.1, 122.7, 127.5, 130.7, 132.2, 133.4, 134.2, 135.3, 136.5, 146.6, 186.9, 187.6; FTIR (neat, cm^{-1}) 3022, 2926, 2830, 1670, 1563, 1427, 1356, 1292, 1208, 1158; HRMS (ESI) *m*/*z* calcd for $C_{19}H_{21}O_6$ $[M + H]^+$ 345.1338, found 345.1340.

*(R)-2-(2,2-Dimethyl-1,3-dioxolan-4-yl)naphthalene-1,4-dione (**7d**).* Compound **7d** was prepared using (*R*,*E*)-2,2-dimethyl-4-(2-nitrovinyl)-1,3-dioxolane (**6d**) as a starting material to give the product as a yellow thick liquid: 64% yield (165 mg); $[\alpha]_D^{25}$ −32.6 (*c* 0.30, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.21 (s, 3H), 1.36 (s, 3H), 3.82−4.12 (m, 2H), 4.30−4.34 (m, 1H), 7.06 (s, 1H), 7.87−7.91 (m, 2H), 8.15−8.19 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.3, 27.3, 74.9, 82.6, 111.1, 120.9, 129.1, 130.9, 132.1, 133.3, 134.3, 135.3, 136.4, 148.8, 185.4, 186.4; FTIR (neat, cm^{-1}) 3052, 2926, 2830, 1668, 1563, 1432, 1356, 1292, 1224, 1162; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{15}O_4[M + H]^+$ 259.0970, found 259.0972.

General Procedure for the Synthesis of Isoflavanone (9a−k). Salicylaldehyde derivative (**8**, 1.0 mmol) and nitroolefin (**3**,1.5 mmol) were added in dry DCM (5 mL) in the presence of thiazolium bromide **2c** (9 mol %) and activated 4 Å MS (300 mg) under a nitrogen atmosphere, and the mixture was stirred for 30 min. DABCO (20 mol %) was added to the reaction mixture, and the mixture was stirred at ambient temperature until the reaction was completed. The reaction was monitored by TLC. The post reaction mixture was filtered through a Celite bed, and the filtrate was extracted with EtOAc (2 × 15 mL). The organic portion was washed with water (3 × 10 mL) and brine (1 × 10 mL). It was dried over Na_2SO_4, filtered, and evaporated to dryness in a rotary evaporator under reduced pressure at room temperature. The crude product was chromatographed on silica gel (60−120 mesh) with ethyl acetate−petroleum ether (10−30%, v/v) as an eluent, which afforded the corresponding isoflavanones.

*3-Phenylchroman-4-one (**9a**).* Compound **9a** was prepared using salicyladehyde (**8a**) and *β*-nitrostyrene (**3a**) as starting materials to give the product as a yellow solid: 72% yield (161 mg); mp 78−80 °C (lit.[33] 77−78 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.99−4.06 (m, 1H), 4.65−4.69 (m, 2H), 7.20−7.34 (m, 5H), 7.49−7.54 (m, 2H), 7.94−8.02 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.9, 71.5, 119.8, 121.7, 123.0, 127.8, 128.4, 128.5, 128.9, 134.5, 135.8, 159.8, 191.3; FTIR (KBr, cm^{-1}) 3012, 2862, 1705, 1582, 1415, 1306, 1248, 1206; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{13}O_2[M + H]^+$ 225.0916, found 225.0915.

*6-Chloro-3-phenylchroman-4-one (**9b**).* Compound **9b** was prepared using 5-chlorosalicylaldehyde (**8b**) and *β*-nitrostyrene (**3a**) as starting materials to give the product as a yellow solid: 82% yield (211 mg); mp 100−102 °C (lit.[33] 99−101 °C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.87−3.92 (m, 1H), 4.56−4.60 (m, 2H), 6.87−6.91 (m, 1H), 7.15−7.18 (m, 3H), 7.22−7.27 (m, 2H), 7.27−7.38 (m, 1H), 7.82 (t, *J* = 5.7 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.9, 71.5, 119.5, 121.7, 126.9, 127.1, 126.9, 128.4, 128.4, 128.9, 134.4, 135.8, 159.9, 191.0; FTIR (KBr, cm^{-1}) 3016, 2862, 1686, 1575, 1425, 1316, 1246, 1210, 786, 667; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{12}ClO_2$ $[M + H]^+$ 259.0526, found 259.0528 (one of the major peaks).

*6-Bromo-3-phenylchroman-4-one (**9c**).* Compound **9c** was prepared using 5-bromosalicylaldehyde (**8c**) and *β*-nitrostyrene (**3a**) as starting materials to give the product as a yellow solid: 78% yield (235 mg); mp 110−112 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.99 (t, *J* = 14.4 Hz, 1H), 4.67 (d, *J* = 7.5 Hz, 2H), 6.92 (d, *J* = 8.7 Hz, 1H), 7.25−7.29 (m, 3H), 7.31−7.39 (m, 3H), 7.57 (dd, *J* = 8.8 Hz, 2.7 Hz, 1H), 8.06 (d, *J* = 2.4 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.8, 71.4, 114.2, 119.9, 122.2, 127.9, 128.4, 128.9, 130.0, 134.4, 138.6, 160.4, 190.8; FTIR (KBr, cm^{-1}) 3022, 2872, 1688, 1602, 1585, 1475, 1316, 1286, 1216, 1146, 1035, 1010, 855, 758; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{12}BrO_2[M + H]^+$ 303.0021, found 303.0022 (one of the major peaks).

*8-Bromo-6-chloro-3-phenylchroman-4-one (**9d**).* Compound **9d** was prepared using 3-bromo-5-chlorosalicylaldehyde (**8d**) and *β*-nitrostyrene (**3a**) as starting materials to give the product as a yellow solid: 74% yield (247 mg); mp 112−114 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.92−3.99 (m, 1H), 4.68−4.76 (m, 2H), 7.17−7.20 (m, 2H), 7.23−7.34 (m, 3H), 7.67 (d, *J* = 2.4 Hz, 1H), 7.81 (d, *J* = 2.4 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.5, 71.9, 112.3, 122.3, 126.4, 127.2, 128.1, 128.5, 129.0, 133.7, 138.5, 156.5, 190.2; FTIR (KBr, cm^{-1}) 3052, 2877, 1686, 1592, 1471, 1313, 1284, 1218, 1144, 1036, 1015, 857, 768, 622; HRMS (ESI) *m*/*z* $[M + H]^+$ calcd for $C_{15}H_{11}BrClO_2$ 336.9631, found 336.9632 (one of the major peaks).

*6,8-Dichloro-3-phenylchroman-4-one (**9e**).* Compound **9e** was prepared using 3,5-dichlorosalicylaldehyde (**8e**) and *β*-nitrostyrene (**3a**) as starting materials to give the product as a yellow thick liquid: 76% yield (221 mg); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.01−4.06 (m, 1H), 4.75−4.79 (m, 2H), 7.24−7.27 (m, 2H), 7.30−7.41 (m, 3H), 7.56−7.58 (m, 1H), 7.82−7.84 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.6, 71.9, 122.4, 123.7, 125.7, 126.8, 128.1, 128.4, 128.6, 129.0, 133.7, 135.5, 155.7, 190.2; FTIR (neat, cm^{-1}) 3082, 2906, 2867, 1684, 1572, 1473, 1315, 1287, 1228, 1025, 662, 585; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{11}Cl_2O_2$ $[M + H]^+$ 293.0136, found 293.0135 (one of the major peaks).

*6-Chloro-3-(4-fluorophenyl)chroman-4-one (**9f**).* Compound **9f** was prepared using 5-chlorosalicylaldehyde (**8b**) and 4-fluoro-*β*-nitrostyrene (**3b**) as starting materials to give the product as a yellow thick liquid: 67% yield (185 mg); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.38 (d, *J* = 12.1 Hz, 1H), 4.41−4.67 (m, 1H), 4.67−4.74 (m, 1H), 6.85−7.01 (m, 2H), 7.34−7.41 (m, 2H), 7.54−7.59 (m, 1H), 7.80−7.81 (m, 1H), 7.91−7.93 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.2, 73.7, 115.4, 115.9, 116.0, 119.7, 125.7, 126.8, 127.5, 127.7, 127.8, 127.9, 130.3, 130.5, 130.6, 133.9, 136.7, 152.9, 159.7, 164.5, 193.2; FTIR (neat, cm^{-1}) 3082, 2908, 2868, 1688, 1582, 1483, 1355, 1267, 1065, 682, 575; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{11}ClFO_2[M + H]^+$ 277.0432, found 277.0435 (one of the major peaks).

*6-Bromo-3-(4-fluorophenyl)chroman-4-one (**9g**).* Compound **9g** was prepared using 5-bromosalicylaldehyde (**8c**) and 4-fluoro-*β*-nitrostyrene (**3b**) as starting materials to give the product as a yellow thick liquid: 71% yield (226 mg); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.88−3.93 (m, 1H), 4.55−4.63 (m, 2H), 6.86 (d, *J* = 9.1 Hz, 1H), 6.95−7.01 (m, 2H), 7.15−7.19 (m, 2H), 7.51 (dd, *J* = 9.1 Hz, 3.6 Hz, 1H), 7.97 (d, *J* = 3.6 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.1, 71.3, 114.3, 115.7, 116.0, 119.9, 122.0, 130.0, 130.1, 138.7, 160.3, 160.7, 190.7; FTIR (neat, cm^{-1}) 3026, 2870, 1688, 1622, 1580, 1472, 1326, 1286, 1210, 1146, 1035, 1012, 875, 762; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{11}BrFO_2$ $[M + H]^+$ 320.9926, found 320.9928 (one of the major peaks).

*6-Chloro-3-(2,6-difluorophenyl)chroman-4-one (**9h**).* Compound **9h** was prepared using 5-chlorosalicylaldehyde (**8b**) and 2,6-difluoro-*β*-nitrostyrene (**3g**) as starting materials to give the product as a yellow thick liquid: 75% yield (220 mg); ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.43−4.49 (m, 2H), 4.57 (d, *J* = 13.2 Hz, 1H), 6.74 (d, *J* = 8.7 Hz, 1H), 6.82−6.91 (m, 1H), 7.10−7.27 (m, 2H), 7.34−7.39 (m, 1H), 7.84 (d, *J* = 2.4 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 43.1, 69.4, 110.2, 111.5, 111.9, 118.2, 119.6, 120.8, 121.5, 126.8, 127.0, 127.1, 127.3, 129.9, 130.1, 130.2, 131.3, 135.9, 148.9, 159.8, 160.2, 163.0, 163.1, 188.8; FTIR (neat, cm^{-1}) 3086, 2928, 2888, 1686, 1585, 1485, 1358, 1268, 1066, 683, 578; HRMS (ESI) *m*/*z* calcd for $C_{15}H_{10}ClF_2O_2$ $[M + H]^+$ 295.0337, found 295.0338 (one of the major peaks).

*8-Methyl-3-phenylchroman-4-one (**9i**).* Compound **9i** was prepared using 2-hydroxy-3-methylbenzaldehyde (**8f**) as a starting material to give the product as a thick liquid: 66% yield (156 mg); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.15 (s, 3H), 3.99 (t, *J* = 4.8 Hz, 1H), 4.66 (d, *J* = 15 Hz, 2H), 6.81 (t, *J* = 7.5 Hz, 1H), 7.27 (d, *J* = 7.5 Hz, 2H), 7.34−7.44 (m, 2H), 7.47−7.55 (m, 1H), 7.77 (d, *J* = 8.1 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.8, 50.0, 71.8, 119.8, 126.6, 128.3, 128.8, 129.6, 130.0, 131.2, 133.5, 134.3, 136.2, 137.7, 159.8,

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192.3; FTIR (KBr, cm^{-1}) 3014, 2863, 1707, 1580, 1417, 1308, 1249, 1204; HRMS (ESI) m/z calcd for $C_{16}H_{15}O_2$ $[M + H]^+$ 239.1072, found 239.1077.

*8-Methoxy-3-phenylchroman-4-one (**9j**).* Compound **9j** was prepared using 2-hydroxy-3-methoxybenzaldehyde (**8g**) as a starting material to give the product as a thick liquid: 60% yield (153 mg); ^1H NMR (300 MHz, $CDCl_3$) δ 3.60 (s, 3H), 3.89 (t, J = 4.8 Hz, 1H), 4.36 (d, J = 8.7 Hz, 2H), 6.9 (t, J = 8.1 Hz, 1H), 7.10−7.20 (m, 2H), 7.53 (t, J = 7.2 Hz, 2H), 7.61−7.63 (m, 1H), 7.86−7.89 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 51.9, 56.1, 71.0, 117.8, 119.4, 120.6, 124.4, 128.3, 128.8, 129.6, 130.0, 134.3, 136.2, 148.1, 151.5, 192.2; FTIR (KBr, cm^{-1}) 3029, 2845, 1709, 1585, 1412, 1316, 1258, 1216; HRMS (ESI) m/z calcd for $C_{16}H_{15}O_3$ $[M + H]^+$ 255.1021, found 255.1017.

*6-Chloro-3-p-tolylchroman-4-one (**9k**).* Compound **9k** was prepared using 5-bromosalicylaldehyde (**8c**) as a starting material to give the product as a thick liquid: 64% yield (174 mg); ^1H NMR (400 MHz, $CDCl_3$) δ 2.34 (s, 3H), 3.92−3.96 (m, 1H), 4.63−4.65 (m, 2H), 6.96 (d, J = 8.8 Hz, 1H), 7.12−7.21 (m, 4H), 7.40−7.43 (m, 1H), 7.89 (d, J = 2.56 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.1, 51.6, 71.6, 119.6, 121.8, 127.0, 127.1, 128.3, 129.7, 131.3, 135.8, 137.7, 160.0, 191.3; FTIR (KBr, cm^{-1}) 2897, 1687, 1455, 1336, 1157, 680; HRMS (ESI) m/z calcd for $C_{16}H_{14}ClO_2$ $[M + H]^+$ 273.0682, found 273.0680 (one of the major peaks).

*(R)-(−)-3-((3aR,5S,6S,6aR)-6-(Benzyloxy)-2,2-dimethyltetrahydrofuro[2,3-d][1,3]dioxol-5-yl)chroman-4-one (**10a**).* Compound **10a** was prepared using (3a*R*,5*R*,6*S*,6a*R*)-6-(benzyloxy)-2,2-dimethyl-5-((*E*)-2-nitrovinyl)tetrahydrofuro[2,3-*d*]-[1,3]dioxole (**6a**) as a starting material to furnish the product as a thick liquid: 50% yield (199 mg); $[\alpha]_D^{25}$ −62.9 (c 0.10, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) 1.28 (s, 3H), 1.46 (s, 3H), 3.64−3.77 (m, 2H), 3.77−3.81 (m, 2H), 4.01−4.12 (m, 4H), 4.56−4.60 (m, 2H), 4.66 (d, J = 11.7 Hz, 2H), 5.89 (d, J = 3.6 Hz, 1H), 7.28−7.38 (m, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.9, 26.3, 51.5, 68.6, 71.9, 79.6, 81.5, 81.9, 104.8, 111.5, 116.9, 119.2, 127.5, 127.7, 128.3, 137.2, 140.8, 159.9, 190.8; FTIR (KBr, cm^{-1}) 3075, 2965, 2855, 1678, 1561, 1425, 1351, 1286, 1208, 1152; HRMS (ESI) m/z calcd for $C_{23}H_{25}O_6$ $[M + H]^+$ 397.1651, found 397.1650.

*(R)-(−)-6-Chloro-3-((3aR,5S,6S,6aR)-2,2-dimethyl-6-(methylperoxy)tetrahydrofuro[2,3-d][1,3]dioxol-5-yl)chroman-4-one (**10b**).* Compound **10b**, was prepared (3a*R*,5*R*,6*S*,6a*R*)-6-methoxy-2,2-dimethyl-5-((*E*)-2-nitrovinyl)tetrahydrofuro[2,3-*d*]-[1,3]dioxole (**6b**) as a starting material to give the product as a colorless thick liquid: 18% yield (64 mg); $[\alpha]_D^{25}$ −78.5 (c 0.10, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) δ 1.13 (s, 3H), 3.27 (s, 3H), 3.67 (t, J = 11.7 Hz, 1H), 3.91 (d, J = 8.1 Hz, 1H), 4.29−4.56 (m, 4H), 5.69 (s, 1H), 6.99 (d, J = 8.4 Hz, 1H), 7.18 (s, 1H), 7.25 (d, J = 5.7 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.3, 52.1, 57.6, 78.7, 79.8, 80.9, 83.1, 111.8, 116.0, 121.1, 124.7, 128.9, 131.1, 134.9, 159.1, 192.8; FTIR (KBr, cm^{-1}) 3032, 2926, 2840, 1680, 1573, 1425, 1354, 1290, 1209, 1168; HRMS (ESI) m/z calcd for $C_{17}H_{20}ClO_6$ $[M + H]^+$ 355.0948, found 355.0951 (one of the major peaks).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.8b01503.

Spectra of the ESI-MS kinetic study and NMR of new compounds (PDF)

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Notes

The authors declare no competing financial interest.

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