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Microwave-assisted manganese(III) acetate based oxidative cyclizations of alkenes with β-ketosulfones

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ABSTRACT

The microwave-assisted synthesis of 5-(4-nitrophenyl)-2-phenyl-4-(phenylsulfonyl)-2,3-dihydrofuran (**5a**) was performed via manganese(III) acetate based oxidative cyclization of 1-(4-nitrophenyl)-2-(phenylsulfonyl)ethanone (**3a**) with vinylbenzene (**4a**). This new protocol was applied to four sulfone derivatives (**3a–d**), using vinylbenzene (**4a**) and diphenylethene (**4b**), affording a series of 2,3-dihydrofurans (**5a–d**, **6a–d**) in moderate to good yields (26–55%). Similar methodology, applied on allylbenzene (**4c**), surprisingly, led to dehydronaphthalene derivatives (**7a–d**) in moderate yields. The unexpected mechanism and the role of allylbenzene (**4c**) are herein discussed.

1. Introduction

Studies of Mn(III)-based oxidative free-radical cyclizations have been extensively explored over the past 40 years.[1] These cyclizations have been applied on a broad variety of acidic compounds such as malonates, 1,3-diketones, and acetoacetates.

However, β-keto sulfones' reactivity with alkenes and Mn(III) acetate, in order to obtain 2,3-dihydrofurans, was little investigated,[2] although dihydrofuran derivatives, substituted with a sulfonyl group, have recently attracted considerable interest because of their promising utility as building blocks in asymmetric synthesis of a wide variety of valuable compounds.[3]

The few examples of oxidative cyclizations of active methylene compounds bearing a sulfone moiety reported in the literature are always time consuming (from 12 to 26 h).[2] This limitation added to the moderate yields of such reactions has limited the feasibility of β-ketosulfones' oxidative cyclizations.

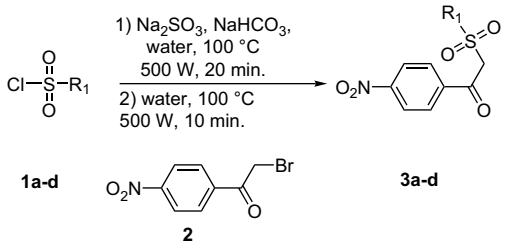
It appears that the reaction mixtures including manganese(III) acetate are good candidates for the microwave irradiation methodology, in spite of the few number of publications in their concern.[4]

Therefore, microwave irradiation could allow rapid heating, efficient solubilization of $Mn(OAc)_3$ in acetic acid, and drastically reduce reaction time. We propose herein a new reproducible microwave-assisted synthesis conducting to dihydrofuran derivatives with vinylbenzene and 1,1-diphenylethene, and to tetrahydronaphthalene derivatives with allylbenzene, which certainly involves two separate mechanisms, depending on the alkene.

2. Results and discussion

Several nitrosulfones (**3a–d**) were synthesized using a previously reported method.[5]

Thus, an aqueous solution of sodium sulfite, sodium bicarbonate, and sulfonyl chlorides (**1a–d**) was irradiated at 500 W for 20 min in a microwave oven, giving the corresponding sodium sulfinates. An ethanolic solution of 2-bromo-4′-nitroacetophenone (**2**) was then added and the reaction mixture was irradiated for 10 min to give the corresponding sulfones (**3a–d**) (Scheme 1).



Scheme 1.

The β-ketosulfone derivatives thus obtained are presented in Table 1. All these products (**3a–d**) bear an active methylene group next to the carbonyl one, which allows manganese(III) acetate oxidative cyclizations.

Following a previously described procedure,[6] manganese(III) acetate was dissolved in glacial acetic acid at 80 °C under nitrogen atmosphere. To this solution, 1-(4-nitrophenyl)-2-(phenylsulfonyl)ethanone (**3a**) and vinylbenzene (**4a**) were added and the reaction was monitored by TLC.

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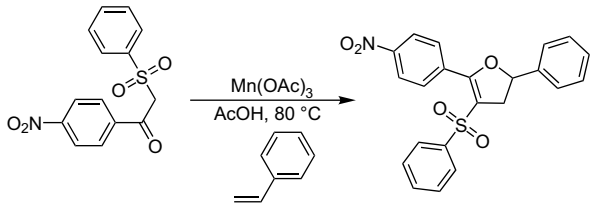
Table 1
Microwave-assisted synthesis of β-ketosulfones

Compound	R_1	Yield[a] (%)
3a	C_6H_5–	90
3b	*p*-CH_3–C_6H_4–	69
3c	*p*-Cl–C_6H_4–	51
3d	*n*-C_4H_9	84

[a] Yield of isolated product based on 2-bromo-4′-nitroacetophenone **2**.

The oxidative cyclization product, 2,3-dihydrofuran (**5a**), could be obtained (Scheme 2) in moderate yield (21%).



3a **4a** **5a**

Scheme 2.

For the sake of improving the reaction yield conducting to **5a**, we next investigated the effect of $Cu(OAc)_2$ addition and microwave irradiation.

As shown in Table 2, $Cu(OAc)_2$ addition not only improved the yield from 21% to 31% (entries 1 and 2), but also simplified purification by decreasing the amount of inseparable secondary products. This difference is attributed to the relative ability of Mn(III) and Cu(II) ions to oxidize alkyl radicals into the corresponding carbocations, 350 times faster than with Mn(III) alone.[7]

Table 2
Oxidative cyclization optimization of **3a** with **4a**

Entry[b]	$Cu(OAc)_2$	Microwave irradiation	Time (min)	Yields[a] **5a** (%)
1	None[c]	None	180	21
2	1 equiv[c]	None	180	31
3	1 equiv	300 W	1+5[d]	14
4	1 equiv	200 W	15+15[d]	30
5	1 equiv	200 W	15+30[d]	32

[a] Yield of isolated product based on the sulfone **3a**.
[b] All reactions were carried out with 2.1 equiv of manganese(III) acetate and 3 equiv of alkene **4a**.
[c] Reaction carried out under N_2 atmosphere.
[d] Dissolution times of $Mn(OAc)_3$ and $Cu(OAc)_2$+Reaction times after sulfone **3a** and alkene **4a** addition.

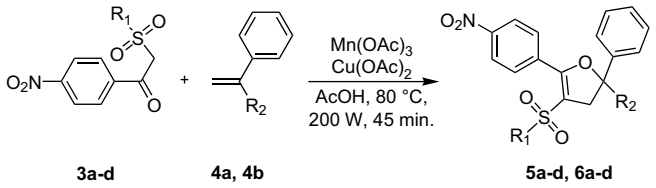
The literature reports that Mn(III)-induced thiyl radical reaction is improved by microwave irradiation.[4] Applied on β-ketosulfones, we found that microwave irradiation can reduce reaction times from 3 h to 45 min (entries 3–5).

Overall, the best experimental conditions are to carry out this reaction under microwave irradiation (200 W, 80 °C, 45 min), in the presence of 2.1 equiv of $Mn(OAc)_3$ and 1.0 equiv of $Cu(OAc)_2$.

A plausible reaction mechanism for this oxidative cyclization is suggested in Scheme 3.[1,5] According to this mechanism, the interaction of $Mn(OAc)_3$ with the enol form of 1-(4-nitrophenyl)-2-(phenylsulfonyl)ethanone (**3a**) could afford manganese(III)-enolate complex **A**. Then, as previously described for α-unsubstituted compounds,[8] the reaction of structure **A** and the alkene (**4a**) formed a carbon–carbon bond with a benzylic radical **B**. A second equivalent of $Mn(OAc)_3$ or $Cu(OAc)_2$ could be used to oxidize the newly formed radical in order to give rise to a carbocation **C**. Finally, an intramolecular cyclization could give the 2,3-dihydrofuran (**5a**).

Under the optimized reaction conditions, we next investigated Mn(III)-mediated oxidative cyclization of previously synthesized sulfones (**3a–d**) with two alkenes: vinylbenzene (**4a**) and 1,1-diphenylethene (**4b**) (Scheme 4). The results are summarized in Table 3.

The reactions of sulfones (**3a–d**) with vinylbenzene (**4a**) gave moderate yields (26–32%) of 2,3-dihydrofurans (**5a–d**). However, when the reaction was conducted with 1,1-diphenylethylene (**4b**),



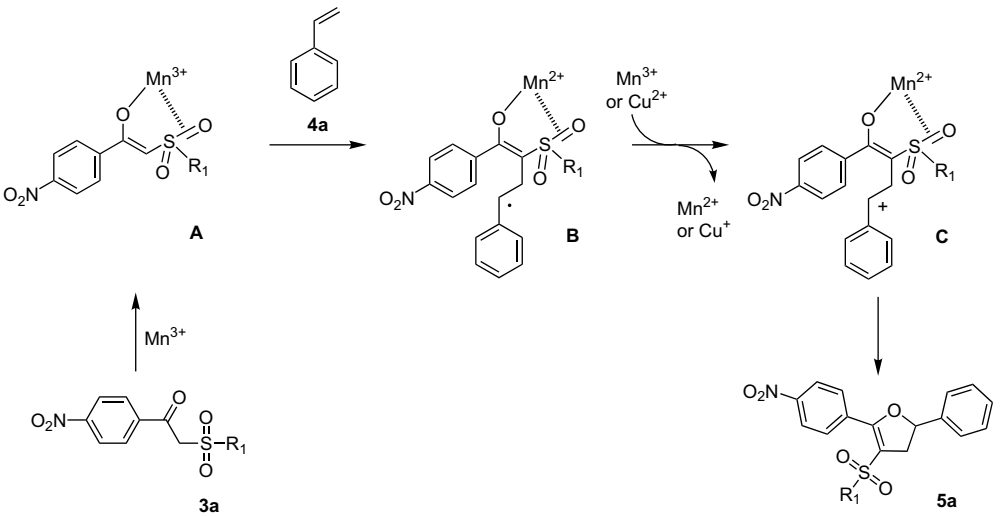
3a-d **4a, 4b** **5a-d, 6a-d**

Scheme 4.

Table 3
Oxidative cyclizations mediated by $Mn(OAc)_3$

Entry	R_1	R_2	Yield[a] (%)
1	C_6H_5–	H–	**5a** (32)
2	*p*-CH_3–C_6H_4–	H–	**5b** (30)
3	*p*-Cl–C_6H_4–	H–	**5c** (26)
4	*n*-C_4H_9	H–	**5d** (28)
5	C_6H_5–	C_6H_5–	**6a** (48)
6	*p*-CH_3–C_6H_4–	C_6H_5–	**6b** (55)
7	*p*-Cl–C_6H_4–	C_6H_5–	**6c** (50)
8	*n*-C_4H_9	C_6H_5–	**6d** (54)

[a] Yield of isolated product based on the corresponding sulfones **3a–d**.



Scheme 3.

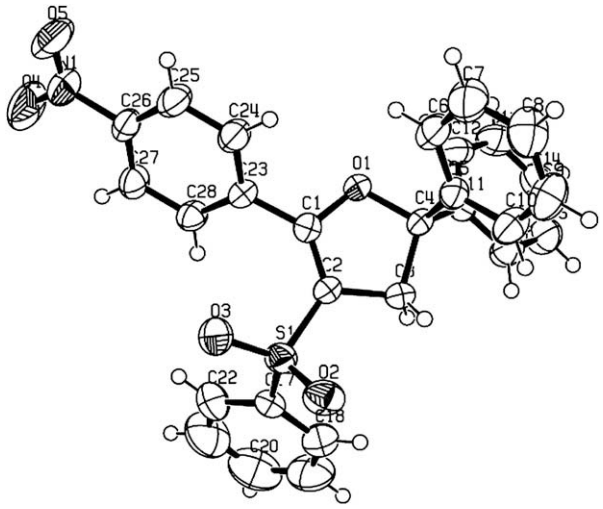


Figure 1. ORTEP view of compound **6a**.

the yields of the corresponding 2,3-dihydrofuran derivatives (**6a**–**d**) were significantly improved (48–55%). Consequently, this could indicate that 1,1-diphenylethylene is more reactive than vinylbenzene toward oxidative cyclization of β-ketosulfones.

This higher reactivity can be explained by the better stability of the intermediate product resulting from the reaction of 1,1-diphenylethylene on the α-carbon radical of the sulfone. A more stable tertiary carbon radical is formed by this way, conjugated with two phenyl groups, while a secondary radical, conjugated with only one phenyl group, is formed with vinylbenzene.

The structure of dihydrofuran products was confirmed by X-ray diffraction analysis on 5-(4-nitrophenyl)-2,2-diphenyl-4-(phenylsulfonyl)-2,3-dihydrofuran (**6a**, Fig. 1).

In each series (**5a**–**d** and **6a**–**d**), yields were slightly different, so we can also conclude that the sulfone moiety has almost no influence on the oxidative cyclization of β-ketosulfones.

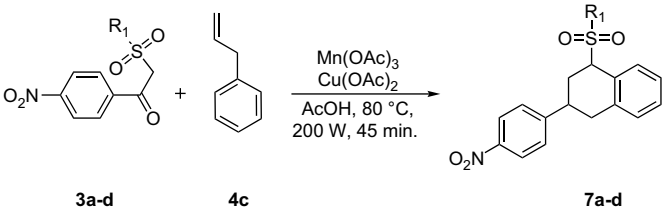
In allylic series, the reaction of allylbenzene (**4c**) with sulfones (**3a**–**d**) did not give dihydrofuran derivatives, but surprisingly proceeded to tetraline derivatives (**7a**–**d**) with moderate yields (Scheme 5). These results are summarized in Table 4.

The structure of tetraline products was confirmed by X-ray diffraction analysis on 3-(4-nitrophenyl)-1-(phenylsulfonyl)-1,2,3,4-tetrahydronaphthalene (**7a**, Fig. 2).

In vinylic and diphenylethylenic series, no trace of tetrahydronaphthalenic derivatives was found. Allylbenzene may thus be fully involved in this unexpected mechanism. We can easily assure that the radical formed after the allylbenzene addition on the α-sulfonyl carbon radical is less stable than the radical coming from the vinylbenzene and 1,1-diphenylethene addition.

This could lead to an unexpected reaction, resulting in the formation of the tetraline derivatives as in the allylbenzene series (**7a**–**d**), instead of radical oxidation, followed by intramolecular cyclization.

Several examples in the literature deal with manganese(III) acetate-induced cyclizations with tetrahydronaphthalene



3a-d **4c** **7a-d**

Scheme 5.

Table 4
$Mn(OAc)_3$-mediated reactions in allylic series

Entry	R_1	Yield[a] (%)
1	C_6H_5–	**7a** (32)
2	*p*-CH_3–C_6H_4–	**7b** (30)
3	*p*-Cl–C_6H_4–	**7c** (31)
4	*n*-C_4H_9	**7d** (40)

[a] Yield of isolated product based on the corresponding sulfones **3a**–**d**.

derivatives,[9] but none describes the formation of original compounds such as **7a**–**d**. However, a new manganese(III)-induced radical cascade involving the 1,4-radical aryl migration, as the key step of the transformation, has been reported recently.[10]

From our point of view, this rearrangement may process through a ketonic [5.4]spirocyclic radical intermediate **E** (Scheme 6). As reported in the literature, spirocyclohexadienyl radicals are unstable and rarely isolable, but their formation may be induced by manganese(III) acetate.[11] Moreover, this intermediate can conduct to a rearrangement from arylketone to give acyl or acyloxyl radical.[12] According to this mechanism, in allylic series $Mn(OAc)_3$-mediated reactions begin similar to the ones operated in vinylic and diphenylethylenic series. Then, the obtained *C*-alkylated allylic radical **D**, less stable than the vinylic ones, is not oxidized and adds to the nitrophenyl group to form the spirocyclic intermediate **E**. Ring opening to give acyl radical **F** should occur.

Mn^{3+} assisted oxidation of the acyl radical **F** could also conduct to the carboxylic acid **G**.[13] This intermediate could be then subjected to an oxidation, conducting to the α-sulfonyl radical **I**.

Formation of this α-sulfonyl radical **I** could be followed by homolytic aromatic substitution and by subsequent oxidation of intermediate radical **J** to give the tetrahydronaphthalene derivative **K**. Finally, decarboxylation of **K** could conduct to tetrahydronaphthalene derivatives (**7a**–**d**).

We next investigated the influence of the nitro group on tetraline synthesis (Scheme 7). Therefore, the reaction of allylbenzene (**4c**) with sulfones (**8a**–**c**) gave moderate yields (20–26%) of *C*-alkylated sulfones (**9a**–**c**) (Table 5).

The nitro group appears to be necessary for the tetraline synthesis depicted in Scheme 6. We can suppose that the formation of spirocyclic intermediate **E** depends on the presence of a nitro group.

Influence of the substitution on the allyl group was also studied. Reaction of 1-(4-nitrophenyl)-2-(phenylsulfonyl) ethanone (**3a**) with (2-methylallyl)benzene (**4d**) proceeded to 2,3-dihydrofuran derivative (**10a**) in good yields (84%) (Scheme 8). We can conclude that the formation of tetraline or 2,3-dihydrofuran derivatives by Mn(III)-based oxidative free-radical strategy is directly related to the degree of substitution of allylic bond.

In summary, we performed a new microwave-assisted synthesis, which decreases the reaction times of time-consuming Mn(III)-

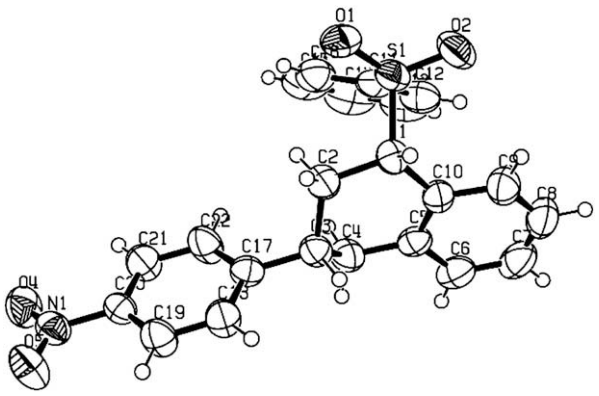
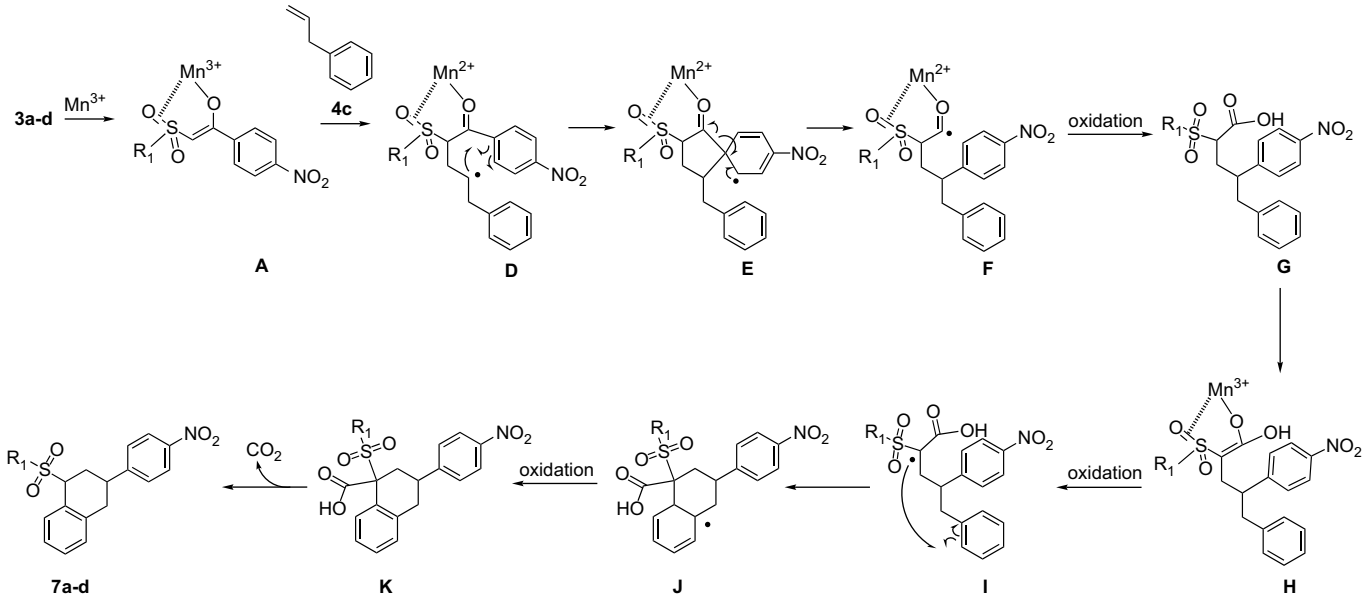
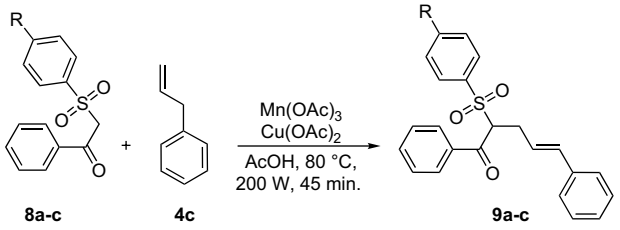


Figure 2. ORTEP view of compound **7a**.



Scheme 6.

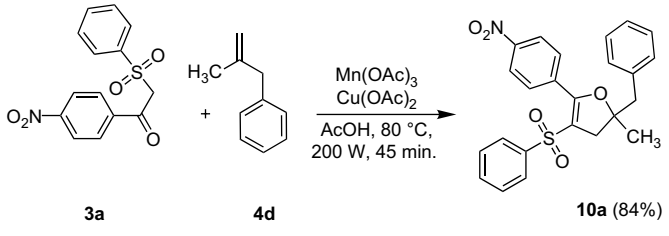


Scheme 7.

Table 5
$Mn(OAc)_3$-mediated reactions in allylic series

Entry	R	Yield[a] (%)
1	H–	**9a** (21)
2	Cl–	**9b** (20)
3	CH_3–	**9c** (26)

[a] Yield of isolated product based on the corresponding sulfones **8a–c**.



Scheme 8.

based oxidative free-radical cyclizations. Applied on homogenous series of sulfones and two alkenes, we showed the general character of this protocol. Further studies on other Mn(III) reactions will next be investigated.

We also identified an original Mn(III) induced reaction in allylic series, leading to tetraline derivatives. A hypothetical resulting mechanism was suggested. Effects of the nitro group and of the allylic substitution were also studied, but complementary studies are in progress in order to confirm the mechanism and to extend the reaction to other substrates.

3. Experimental

3.1. General

Microwave-assisted reactions were done in a multimode microwave oven ETHOS Synth Lab Station (Ethos start, Milestone Inc.). Melting points were determined with a B-540 Büchi melting point apparatus. ^1H (200 MHz) and ^{13}C NMR (50 MHz) spectra were recorded on a Bruker ARX 200 spectrometer in $CDCl_3$ at the Service interuniversitaire de RMN de la Faculté de Pharmacie de Marseille. ^1H and ^{13}C NMR chemical shifts (δ) are reported in parts per million with respect to $CDCl_3$ 7.26 (^1H) and 77 ppm (^{13}C). Elemental analysis was carried out at the Spectropole de la Faculté des Sciences et Techniques de Saint-Jérôme. The following adsorbent was used for flash column chromatography: silica gel 60 (Merck, particle size 0.063–0.200 nm, 70–230 mesh ASTM). TLC was performed on 5 cm×10 cm aluminium plates coated with silica gel $60F_{254}$ (Merck) in appropriate solvent. Mass spectra were run on an API-QqToF mass spectrometer. X-ray analyses were performed on a Bruker–Nonius KappaCCD diffractometer with a graphite-monochromated Mo Kα radiation at 293(2) K.

3.2. General procedure for the synthesis of β-ketosulfones

To a solution of sulfonyl chlorides **1a–d** (6.00 mmol) in water (15 mL), sodium sulfite (1.26 g, 10 mmol) and sodium bicarbonate (0.84 g, 10 mmol) were added. The reaction mixture was heated under reflux in a microwave oven under irradiation (500 W, 100 °C) for 20 min. Then, an ethanolic solution of 2-bromo-4′-nitroacetophenone (0.50 g, 2.05 mmol) was added. Heating of the reaction mixture was continued for 10 min under the same conditions. After cooling, the reaction mixture was neutralized with diluted hydrochloric acid. The resulting solution was filtered and the precipitate thus formed was crystallized from the appropriate solvent.

*3.2.1. 2-(Butylsulfonyl)-1-(4-nitrophenyl)ethanone (**3d**)*

Colorless solid, mp 114 °C (CH_2Cl_2/hexane). ^1H NMR ($CDCl_3$), δ: 0.99 (t, J=7.3 Hz, 3H), 1.50 (m, 2H), 1.89 (m, 2H), 3.24 (t, J=7.8 Hz, 2H), 4.60 (s, 2H), 8.20 (d, J=9.0 Hz, 2H), 8.37 (d, J=9.0 Hz, 2H). ^{13}C

NMR ($CDCl_3$), δ: 13.5 (CH_3), 21.6 (CH_2), 23.9 (CH_2), 53.6 (CH_2), 60.1 (CH_2), 124.1 (2CH), 130.5 (2CH), 140.0 (C), 188.1 (C), C–NO_2 not observed in these conditions. Anal. Calcd for $C_{12}H_{15}NO_5S$ (285.32): C, 50.52; H, 5.30; N, 4.91. Found: C, 50.85; H, 5.14; N, 5.03.

3.3. General procedure for $Mn(OAc)_3$-mediated reaction of β-ketosulfones with alkenes

A solution of manganese(III) acetate dihydrate (6.87 mmol, 1.84 g) and copper(II) acetate (3.27 mmol, 0.59 g) in 30 mL of glacial acetic acid was heated under microwave irradiation (200 W, 80 °C) for 15 min, until dissolution. Then, the reaction mixture was cooled down to 50 °C, and a solution of **3a**–**d** (3.27 mmol) and alkenes **4a**–**c** (9.81 mmol) in 5 mL acetic acid was added. The mixture was heated under microwave irradiation (200 W, 80 °C) for 30 min. The reaction mixture was poured into 200 mL of cold water, and extracted with chloroform (3×40 mL). The organic extracts were collected, washed with saturated aqueous $NaHCO_3$ (3×40 mL), and dried ($MgSO_4$). Solvent evaporation was followed by column chromatography (gradient, from chloroform/petroleum ether (1/1) to chloroform/petroleum ether/diethyl ether (5/3/2)), and the product obtained was recrystallized from the appropriate solvent.

*3.3.1. 5-(4-Nitrophenyl)-2-phenyl-4-(phenylsulfonyl)-2,3-dihydrofuran (**5a**)*

Yellow oil. ^1H NMR ($CDCl_3$), δ: 3.18 (dd, J=8.7 and 15.0 Hz, 1H, CH_a), 3.57 (dd, J=10.6 and 15.0 Hz, 1H, CH_b), 5.76 (dd, J=8.7 and 10.6 Hz, 1H, CH), 7.29–7.65 (m, 8H, CH), 7.75–7.79 (m, 2H, CH), 7.95 (d, J=8.9 Hz, 2H, CH), 8.28 (d, J=8.9 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 39.9 (CH_2), 83.4 (CH), 112.9 (C), 122.9 (2CH), 125.7 (2CH), 127.0 (2CH), 128.9 (CH), 129.0 (2CH), 129.2 (2CH), 130.8 (2CH), 133.3 (CH), 134.3 (C), 139.6 (C), 141.0 (C), 149.0 (C), 160.5 (C). Anal. Calcd for $C_{22}H_{17}NO_5S$ (407.44): C, 64.85; H, 4.21; N, 3.44. Found: C, 64.45; H, 4.55; N, 3.09.

*3.3.2. 5-(4-Nitrophenyl)-2-phenyl-4-tosyl-2,3-dihydrofuran (**5b**)*

Yellow oil. ^1H NMR ($CDCl_3$), δ: 2.42 (s, 3H, CH_3), 3.16 (dd, J=8.9 and 15.0 Hz, 1H, CH_a), 3.55 (dd, J=10.8 and 15.0 Hz, 1H, CH_b), 5.74 (dd, J=8.9 and 10.8 Hz, 1H, CH), 7.23–7.39 (m, 7H, CH), 7.65 (d, J=8.3 Hz, 2H, CH), 7.94 (d, J=9.0 Hz, 2H, CH), 8.26 (d, J=9.0 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 21.5 (CH_3), 40.0 (CH_2), 83.3 (CH), 113.2 (C), 122.9 (2CH), 125.7 (2CH), 127.1 (2CH), 128.8 (CH), 128.9 (2CH), 129.8 (2CH), 130.8 (2CH), 134.4 (C), 138.1 (C), 139.6 (C), 144.4 (C), 149.0 (C), 160.0 (C). HMRS (EI): m/z calcd for $C_{23}H_{19}NO_5S$ M+H^+: 422.1057, found: 422.1056.

*3.3.3. 4-(4-Chlorophenylsulfonyl)-5-(4-nitrophenyl)-2-phenyl-2,3-dihydrofuran (**5c**)*

Yellow oil. ^1H NMR ($CDCl_3$), δ: 3.17 (dd, J=8.7 and 14.9 Hz, 1H, CH_a), 3.55 (dd, J=10.7 and 14.9 Hz, 1H, CH_b), 5.78 (dd, J=8.7 and 10.7 Hz, 1H, CH), 7.26–7.54 (m, 7H, CH), 7.70 (d, J=8.5 Hz, 2H, CH), 7.94 (d, J=8.7 Hz, 2H, CH), 8.28 (d, J=8.7 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 39.8 (CH_2), 83.5 (CH), 112.4 (C), 123.0 (2CH), 125.6 (2CH), 128.5 (2CH), 128.7 (CH), 129.0 (2CH), 129.6 (2CH), 130.8 (2CH), 134.1 (C), 139.4 (C), 139.5 (C), 147.2 (C), 149.1 (C), 161.0 (C). HMRS (EI): m/z calcd for $C_{22}H_{16}ClNO_5S$ M+H^+: 442.0510, found: 442.0502.

*3.3.4. 4-(Butylsulfonyl)-5-(4-nitrophenyl)-2-phenyl-2,3-dihydrofuran (**5d**)*

Yellow oil. ^1H NMR ($CDCl_3$), δ: 0.88 (t, J=7.2 Hz, 3H, CH_3), 1.30–1.48 (m, 2H, CH_2), 1.63–1.81 (m, 2H, CH_2), 2.95–3.03 (m, 2H, CH_2), 3.30 (dd, J=8.9 and 15.1 Hz, 1H, CH_a), 3.72 (dd, J=10.8 and 15.1 Hz, 1H, CH_b), 5.86 (dd, J=8.9 and 10.8 Hz, 1H, CH), 7.30–7.51 (m, 5H, CH), 8.00 (d, J=8.9 Hz, 2H, CH), 8.27 (d, J=8.9 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 13.5 (CH_3), 21.4 (CH_2), 24.3 (CH_2), 40.5 (CH_2), 54.7 (CH_2), 83.2 (CH), 111.1 (C), 123.1 (2CH), 125.6 (2CH), 129.0 (CH), 129.1 (2CH), 130.7 (2CH), 134.2 (C), 139.7 (C), 149.1 (C), 161.0 (C). HMRS (EI): m/z calcd for $C_{20}H_{21}NO_5S$ M+H^+: 388.1213, found: 388.1209.

*3.3.5. 5-(4-Nitrophenyl)-2,2-diphenyl-4-(phenylsulfonyl)-2,3-dihydrofuran (**6a**)*

White crystals, mp 232 °C (isopropyl alcohol), ^1H NMR ($CDCl_3$), δ: 3.81 (s, 2H, CH_2), 7.29–7.31 (m, 10H, CH), 7.40–7.61 (m, 3H, CH), 7.68–7.72 (m, 2H, CH), 7.95 (d, J=9.0 Hz, 2H, CH), 8.28 (d, J=9.0 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 45.3 (CH_2), 92.7 (C), 113.2 (C), 123.1 (2CH), 125.5 (4CH), 127.0 (2CH), 128.2 (2CH), 128.6 (4CH), 129.2 (2CH), 130.9 (2CH), 133.3 (CH), 134.4 (C), 141.1 (C), 143.3 (2C), 149.1 (C), 159.3 (C). Anal. Calcd for $C_{28}H_{21}NO_5S$ (483.54): C, 69.55; H, 4.38; N, 2.90. Found: C, 69.57; H, 4.41; N, 2.81.

*3.3.6. 5-(4-Nitrophenyl)-2,2-diphenyl-4-tosyl-2,3-dihydrofuran (**6b**)*

White crystals, mp 226–227 °C (isopropyl alcohol). ^1H NMR ($CDCl_3$), δ: 2.41 (s, 3H, CH_3), 3.80 (s, 2H, CH_2), 7.22–7.30 (m, 12H, CH), 7.58 (d, J=8.2 Hz, 2H, CH), 7.94 (d, J=9.0 Hz, 2H, CH), 8.28 (d, J=9.0 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 21.6 (CH_3), 45.4 (CH_2), 92.5 (C), 113.5 (C), 123.0 (2CH), 125.5 (4CH), 127.1 (2CH), 128.1 (2CH), 128.6 (4CH), 129.8 (2CH), 130.9 (2CH), 134.5 (C), 138.2 (C), 143.4 (2C), 144.3 (C), 149.1 (C), 158.8 (C). Anal. Calcd for $C_{29}H_{23}NO_5S$ (497.56): C, 70.00; H, 4.66; N, 2.82. Found: C, 69.89; H, 4.72; N, 2.68.

*3.3.7. 4-(4-Chlorophenylsulfonyl)-5-(4-nitrophenyl)-2,2-diphenyl-2,3-dihydrofuran (**6c**)*

White crystals, mp 228 °C (ethanol). ^1H NMR ($CDCl_3$), δ: 3.78 (s, 2H, CH_2), 7.26–7.35 (m, 10H, CH), 7.40 (d, J=8.5 Hz, 2H, CH), 7.60 (d, J=8.5 Hz, 2H, CH), 7.95 (d, J=8.6 Hz, 2H, CH), 8.30 (d, J=8.6 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 45.2 (CH_2), 92.9 (C), 112.7 (C), 123.1 (2CH), 125.5 (4CH), 128.3 (2CH), 128.4 (2CH), 128.7 (4CH), 129.5 (2CH), 131.0 (2CH), 134.1 (C), 139.5 (C), 140.0 (C), 143.1 (2C), 149.3 (C), 159.9 (C). Anal. Calcd for $C_{28}H_{20}ClNO_5S$ (517.98): C, 64.93; H, 3.89; N, 2.70. Found: C, 64.98; H, 3.93; N, 2.68.

*3.3.8. 4-(Butylsulfonyl)-5-(4-nitrophenyl)-2,2-diphenyl-2,3-dihydrofuran (**6d**)*

Yellow crystals, mp 168–169 °C (isopropyl alcohol). ^1H NMR ($CDCl_3$), δ: 0.77 (t, J=7.2 Hz, 3H, CH_3), 1.17–1.35 (m, 2H, CH_2), 1.46–1.57 (m, 2H, CH_2), 2.87–2.95 (m, 2H, CH_2), 3.97 (s, 2H, CH_2), 7.33–7.46 (m, 10H, CH), 8.05 (d, J=9.0 Hz, 2H, CH), 8.30 (d, J=9.0 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 13.4 (CH_3), 21.4 (CH_2), 24.4 (CH_2), 46.1 (CH_2), 55.0 (CH_2), 92.5 (C), 111.3 (C), 123.2 (2CH), 125.5 (4CH), 128.3 (2CH), 128.8 (4CH), 130.8 (2CH), 134.3 (C), 143.5 (2C), 149.2 (C), 159.7 (C). Anal. Calcd for $C_{26}H_{25}NO_5S$ (463.55): C, 67.37; H, 5.44; N, 3.02. Found: C, 67.29; H, 5.58; N, 3.01.

*3.3.9. 3-(4-Nitrophenyl)-1-(phenylsulfonyl)-1,2,3,4-tetrahydro naphthalene (**7a**)*

White crystals, mp 180 °C (cyclohexane). ^1H NMR ($CDCl_3$), δ: 2.28–2.95 (m, 5H, $2CH_2$+1CH), 4.70 (dd, J=6.9 and 9.6 Hz, 1H, CH), 7.07–7.67 (m, 11H, CH), 8.19 (d, J=8.8 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 31.3 (CH_2), 36.6 (CH_2), 40.8 (CH), 65.3 (CH), 124.0 (2CH), 126.7 (CH), 126.8 (C), 127.8 (2CH), 128.8 (2CH), 128.9 (2CH), 129.6 (2CH), 131.4 (CH), 133.9 (CH), 136.2 (C), 140.0 (C), 147.0 (C), 151.9 (C). Anal. Calcd for $C_{22}H_{19}NO_4S$ (393.46): C, 67.16; H, 4.87; N, 3.56. Found: C, 66.97; H, 4.99; N, 3.53.

*3.3.10. 3-(4-Nitrophenyl)-1-tosyl-1,2,3,4-tetrahydro naphthalene (**7b**)*

Yellow crystals, mp 194 °C (isopropyl alcohol). ^1H NMR ($CDCl_3$), δ: 2.26–2.97 (m, 5H, $2CH_2$+CH), 2.43 (s, 3H, CH_3), 4.68 (dd, J=7.0 and 9.3 Hz, 1H, CH), 7.07–7.47 (m, 10H, CH), 8.20 (d, J=8.7 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 21.6 (CH_3), 31.4 (CH_2), 36.7 (CH_2), 40.8 (CH), 65.3 (CH), 124.0 (2CH), 126.6 (CH), 126.9 (C), 127.8 (2CH), 128.6 (CH), 128.7 (CH), 129.5 (2CH), 129.6 (2CH), 131.4 (CH), 133.3 (C),

139.9 (C), 144.9 (C), 146.9 (C), 151.9 (C). Anal. Calcd for $C_{23}H_{21}NO_4S$ (407.48): C, 67.79; H, 5.19; N, 3.44. Found: C, 67.42; H, 5.37; N, 3.37.

*3.3.11. 1-(4-Chlorophenylsulfonyl)-3-(4-nitrophenyl)-1,2,3,4-tetrahydronaphthalene (**7c**)*

Yellow crystals, mp 192–194 °C (ethanol). ^{1}H NMR ($CDCl_3$), δ: 2.24–2.99 (m, 5H, $2CH_2$+CH), 4.66–4.75 (dd, J=7.0 and 9.5 Hz, 1H, CH), 7.08–7.50 (m, 10H, CH), 8.21 (d, J=8.8 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 31.4 (CH_2), 36.6 (CH_2), 40.7 (CH), 65.5 (CH), 124.1 (2CH), 126.5 (C), 126.7 (CH), 127.8 (2CH), 128.9 (CH), 129.0 (CH), 129.1 (2CH), 130.9 (2CH), 131.3 (CH), 134.8 (C), 140.0 (C), 140.8 (C), 147.0 (C), 151.6 (C). Anal. Calcd for $C_{22}H_{18}ClNO_4S$ (427.90): C, 61.75; H, 4.24; N, 3.27. Found: C, 61.81; H, 4.29; N, 3.20.

*3.3.12. 1-(Butylsulfonyl)-3-(4-nitrophenyl)-1,2,3,4-tetrahydro naphthalene (**7d**)*

White crystals, mp 125–127 °C (isopropyl alcohol). ^{1}H NMR ($CDCl_3$), δ: 0.91 (t, J=7.2 Hz, 3H, CH_3), 1.32–1.51 (m, 2H, CH_2), 1.71–1.86 (m, 2H, CH_2), 2.34–3.26 (m, 7H), 4.55–4.64 (m, 1H, CH), 7.19–7.23 (m, 1H, CH), 7.30–7.34 (m, 2H, CH), 7.50 (d, J=8.7 Hz, 2H, CH), 7.68–7.72 (m, 1H, CH), 8.23 (d, J=8.7 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 13.5 (CH_3), 21.8 (CH_2), 23.2 (CH_2), 31.3 (CH_2), 37.1 (CH_2), 40.6 (CH), 48.4 (CH_2), 63.4 (CH), 124.1 (2CH), 126.7 (C), 127.1 (CH), 127.9 (2CH), 129.2 (CH), 129.4 (CH), 130.6 (CH), 139.6 (C), 147.0 (C), 151.8 (C). Anal. Calcd for $C_{20}H_{23}NO_4S$ (373.47): C, 64.32; H, 6.21; N, 3.75. Found: C, 64.11; H, 6.32; N, 3.73.

*3.3.13. (E)-1,5-Diphenyl-2-(phenylsulfonyl)pent-4-en-1-one (**9a**)*

White crystals, mp 111 °C (isopropyl alcohol) (Lit. 115.3–115.4 °C).[14] ^{1}H NMR ($CDCl_3$), δ: 2.95–3.05 (m, 2H, CH_2), 5.21 (dd, J=4.8 and 9.8 Hz, 1H, CH), 5.92 (dt, J=7.2 and 15.6 Hz, 1H, CH), 6.40 (d, J=15.6 Hz, 1H, CH), 7.15–7.20 (m, 5H, CH), 7.40–7.66 (m, 6H, CH), 7.80 (d, J=8.2 Hz, 2H, CH), 7.92 (d, J=8.1 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 31.6 (CH_2), 69.4 (CH), 122.9 (CH), 126.1 (2CH), 127.6 (CH), 128.4 (2CH), 128.7 (2CH), 128.9 (2CH), 129.0 (2CH), 129.7 (2CH), 134.0 (CH), 134.1 (CH), 134.3 (CH), 136.3 (C), 136.4 (C), 136.9 (C), 191.8 (C).

*3.3.14. (E)-1-(4-Chlorophenyl)-5-phenyl-2-(phenylsulfonyl)pent-4-en-1-one (**9b**)*

White crystals, mp 142–143 °C (isopropyl alcohol). ^{1}H NMR ($CDCl_3$), δ: 2.91–3.06 (m, 2H, CH_2), 5.12 (dd, J=4.6 and 9.9 Hz, 1H, CH), 5.89 (dt, J=7.1 and 15.8 Hz, 1H, CH), 6.40 (d, J=15.8 Hz, 1H, CH), 7.15–7.22 (m, 5H, CH), 7.42 (d, J=8.6 Hz, 2H, CH), 7.51–7.69 (m, 3H, CH), 7.76–7.81 (m, 2H, CH), 7.89 (d, J=8.6 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 31.7 (CH_2), 69.8 (CH), 122.8 (CH), 126.2 (2CH), 127.7 (CH), 128.5 (2CH), 129.0 (2CH), 129.1 (2CH), 129.8 (2CH), 130.4 (2CH), 134.4 (CH), 134.5 (CH), 135.3 (C), 136.2 (C), 136.4 (C), 140.8 (C), 190.8 (C). Anal. Calcd for $C_{23}H_{19}ClO_3S$ (410.91): C, 67.23; H, 4.66. Found: C, 67.25; H, 4.80.

*3.3.15. (E)-5-Phenyl-2-(phenylsulfonyl)-1-p-tolylpent-4-en-1-one (**9c**)*

White crystals, mp 151–152 °C (isopropyl alcohol). ^{1}H NMR ($CDCl_3$), δ: 2.40 (s, 3H, CH_3), 2.92–3.09 (m, 2H, CH_2), 5.17 (dd, J=4.9 and 9.6 Hz, 1H, CH), 5.91 (dt, J=7.2 and 15.7 Hz, 1H, CH), 6.41 (d, J=15.7 Hz, 1H, CH), 7.18–7.22 (m, 7H, CH), 7.48–7.70 (m, 3H, CH), 7.78–7.86 (m, 4H, CH). ^{13}C NMR ($CDCl_3$), δ: 21.7 (CH_3), 31.7 (CH_2), 69.5 (CH), 123.2 (CH), 126.2 (2CH), 127.6 (CH), 128.4 (2CH), 128.9 (2CH), 129.2 (2CH), 129.5 (2CH), 129.8 (2CH), 134.1 (CH), 134.2 (CH), 134.6 (C), 136.4 (C), 136.5 (C), 145.2 (C), 191.3 (C). Anal. Calcd for $C_{24}H_{22}O_3S$ (390.49): C, 73.82; H, 5.68. Found: C, 74.15; H, 5.80.

*3.3.16. 2-Benzyl-2-methyl-5-(4-nitrophenyl)-4-(phenylsulfonyl)-2,3-dihydrofuran (**10a**)*

Brown crystals, mp 147 °C (isopropyl alcohol). ^{1}H NMR ($CDCl_3$), δ: 1.51 (s, 3H, CH_3), 2.83–3.11 (m, 4H, CH_2), 7.08–7.22 (m, 5H, CH), 7.39–7.56 (m, 5H, CH), 7.75 (d, J=8.6 Hz, 2H, CH), 8.24 (d, J=8.6 Hz, 2H, CH). ^{13}C NMR ($CDCl_3$), δ: 27.1 (CH_3), 41.8 (CH_2), 46.4 (CH_2), 89.1 (C), 112.2 (C), 122.8 (2CH), 126.7 (2CH), 127.0 (CH), 128.3 (2CH), 129.1 (2CH), 130.2 (2CH), 130.5 (2CH), 133.0 (CH), 134.9 (C), 135.3 (C), 141.2 (C), 148.9 (C), 159.8 (C). Anal. Calcd for $C_{24}H_{21}NO_5S$ (435.49): C, 66.19; H, 4.86; N, 3.22. Found: C, 66.17; H, 4.93; N, 3.16.

3.4. X-ray structure determination of compounds 6a and 7a

Crystal data for compound **6a**: $C_{28}H_{21}NO_5S$, colorless prism ($0.2\times0.1\times0.025$ mm^3), M_W=483.52, monoclinic, space group $P2_1/c$ (T=293 K), a=11.3370(3) Å, b=23.5499(6) Å, c=9.7545(2) Å, α=90°, β=114.469(1)°, γ=90°; V=2370.4(1) Å^3, Z=4, D_{calcd}=1.355 g cm^{-1}, μ=0.177 mm^{-1}, F(000)=1008, index ranges $-13\leq h\leq15$, $-31\leq k\leq0$, $-12\leq l\leq0$. θ range=1.73–28.25°, 316 variables and 0 restraints, were refined for 3626 reflections with $I\geq2\sigma_I$ to R=0.0749, GoF=1.103.

Crystal data for compound **7a**: $C_{22}H_{19}NO_4S$ colorless prism ($0.3\times0.15\times0.15$ mm^3), M_W=393.44, monoclinic, space group $P2_1/n$ (T=293 K), a=8.2450(2) Å, b=10.8510(3) Å, c=21.4079(5) Å, α=90°, β=96.838(2)°, γ=90°; V=1901.67(8) Å^3, Z=4, D_{calcd}=1.374 g cm^{-1}, μ=0.199 mm^{-1}, F(000)=824, index ranges $0\leq h\leq10$, $0\leq k\leq14$, $-28\leq l\leq28$. θ range=1.92–28.62°, 253 variables and 0 restraints, were refined for 2889 reflections with $I\geq2\sigma_I$ to R=0.0643, GoF=1.216.

Crystallographic data (excluding structure factors) for the structures **6a** and **7a** have been deposited with the Cambridge Crystallographic Data Centre (CCDC) under the numbers 693923 for **6a** and 693924 for **7a**. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 (0)1223 336033 or e-mail: deposit@ccdc.cam.ac.uk).

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