Studies on the Radical Cyclization of 3-Oxopropanenitriles and Alkenes with Cerium(IV) Ammonium Nitrate in Ether Solvents

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The radical cyclization of 3-oxopropanenitriles **1a**–**1e** and alkenes **2a**–**2g** with cerium(IV) ammonium nitrate (CAN) in ether solvents was investigated (*Tables 1* and *2*). In the optimization study, 1,3-dioxolane, 1,4-dioxane, 1,2-dimethoxyethane, Et_2O, and THF were used as ether-based solvents, and the latter was found to be the most effective solvent in radical cyclizations mediated by cerium(IV). This system (cerium(IV)/THF) was applied to cyclizations of various 3-oxopropanenitriles and 1,3-dicarbonyl compounds with alkenes resulting in the formation of 4,5-dihydrofurans in high yields (*Table 2* and *Scheme 2*). The results of the cerium(IV)/THF radical cyclization were compared with those obtained with manganese(III) acetate/AcOH; the cerium(IV)/THF system turned out to be much more efficient.

Introduction. – During the last three decades, manganese(III) acetate dihydrate (MAH) [1] and cerium(IV) ammonium nitrate (CAN) [2] have been used as efficient radical oxidants. These oxidants have the ability for a one-electron transfer and are used in organic synthesis for constructing C–C bonds. Both CAN and MAH are well known for dihydrofuran formation by radical cyclization of 1,3-dicarbonyl compounds with alkenes. Dihydrofurans show a wide range of biological activities and form the basic structure of many natural compounds [3].

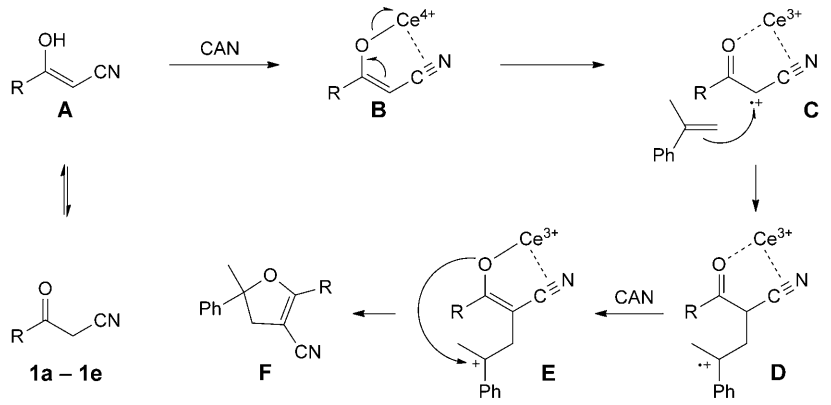
Our research group has studied the radical cyclization of 1,3-dicarbonyl compounds and 3-oxopropanenitriles with alkenes, alkynes, unsaturated amides, and dienes in the presence of manganese(III) acetate [4]. Very recently, we have reported that some 4,5-dihydrofuran-3-carbonitriles show antibacterial and antifungal activity [5]. These carbonitriles are available by oxidative cyclization of 3-oxopropanenitriles with conjugated alkenes [4f][4g] and unsaturated amides [4h]. In these reactions, MAH/AcOH gives good results, whereas CAN is not efficient when MeOH or MeCN are used as solvents. Hence, we performed an optimization using ether-based solvents and CAN which were more effective. We applied the optimized conditions (CAN/THF, 40–60°) to a study of the cyclization of 3-oxopropanenitriles and 1,3-dicarbonyl compounds with alkenes. Additionally, we compared cyclizations induced by CAN/THF and MAH/AcOH. The CAN/THF method gave 4,5-dihydrofurans in high yields.

Results and Discussion. – All 3-oxopropanenitriles were prepared according to [4g][4h][6]. The 1,1-diphenylbut-1-ene (**2e**) [7], 1,1-bis(4-fluorophenyl)ethene (**2f**) [8], and 1,1-bis(4-methylphenyl)ethene (**2g**) [9] were synthesized by dehydration of the corresponding alcohols obtained from *Grignard* reactions of suitable arylmagnesium bromides and ketones. The other alkenes, CAN, and reagents are commercial materials

and were purchased in highest purity. Crude products were purified by column chromatography or/and prep. thin-layer chromatography (TLC). All novel compounds were characterized by IR, ^{1}H- and ^{13}C-NMR, MS, and microanalysis. The other products were characterized by ^{1}H-NMR.

The proposed mechanism for the radical cyclization of 3-oxopropanenitriles with alkenes mediated by CAN and the formation of 4,5-dihydrofuran-3-carbonitriles is displayed in *Scheme 1*. According to this mechanism, [Ce^{IV}(enolato)] complex **B** is formed with the enol form **A** of 3-oxopropanenitriles **1a**–**1e** and CAN. While Ce^{4+} is reduced to Ce^{3+}, a radical at C(α) is formed resulting in structure **C**. The radical intermediate **D** is obtained by an electrophilic radical addition of **C** on the alkene. A [Ce^{3+}(enolato)] complex is formed by removing H–C(α) from structure **D**, and the radical is oxidized to carbocation **E** with CAN. The intramolecular cyclization of **E** forms 4,5-dihydrofuran-3-carbonitrile **F**.

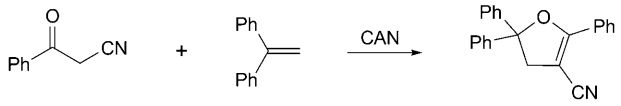
Scheme 1. *Mechanism for the Formation of 4,5-Dihydrofuran-3-carbonitriles*



The synthesis of 4,5-dihydro-2,5,5-triphenylfuran-3-carbonitrile (**3a**) was used as model reaction. This compound **3a** was previously obtained by cyclization of 3-phenyl-3-oxopropanenitrile (**1a**) with 1,1-diphenylethene (**2a**) mediated by MAH in 65% yield [10]. For this model reaction, 1,3-dioxolane, 1,4-dioxane, 1,2-dimethoxyethane, Et_2O, and THF were used as ether solvents as well as MeOH and MeCN, which are traditionally used in reactions of CAN. The syntheses of **3a** were performed with a molar ratio **1a**/**2a**/CAN of 1.2 : 1 : 3, under N_2 at different temperatures for 10 min. The results are given in *Table 1*.

The formation of **3a** with CAN in MeOH at 0° and 60° failed, and compound **3a** could not be isolated. Dihydrofuran **3a** was formed in low yields in MeCN under the same reaction conditions. However, when 1,3-dioxolane and 1,4-dioxane were used at 40–50°, **3a** was obtained in 52 and 83% yield, respectively. At higher temperatures, lower yields were observed. In 1,2-dimethoxyethane at 40–50°, the yield of **3a** amounted to 73%. On the other hand, product **3a** was obtained in 84% yield in Et_2O under reflux for 24 h instead of 10 min (due to the poor solubility of CAN). The optimum yield of 97% was obtained in THF at 40–50° after 10 min reaction time. These results indicated that ether solvents can be used more efficiently in reactions of

Table 1. *Solvent- and Temperature-Optimization Study of the Radical Cyclization*



1a **2a** **3a**

Solvent	T [°]	Yield [%][a])	Solvent	T [°]	Yield [%][a])
MeOH	0	–	1,3-dioxolane	60–70	48
MeOH	60	–	1,4-dioxane	40–50	83
MeCN	0	23	1,4-dioxane	60–70	52
MeCN	60	46	1,2-dimethoxyethane	40–50	73
1,3-Dioxolane	40–50	52	Et_2O	36	84
1,3-Dioxolane	50–60	50	THF	40–50	97

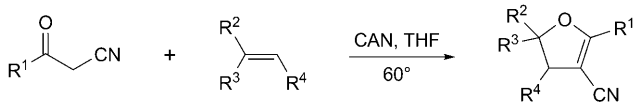
[a]) Yield of isolated product based on alkene **2a**.

CAN. These optimum conditions were applied to the reactions of various 3-oxopropanenitriles, and the results were compared to the reactions performed with MAH/AcOH (*Table 2*).

While the radical cyclization of 3-(furan-2-yl)-3-oxopropanenitrile (**1b**) mediated by MAH gave **3b** in 50% yield, the new method (CAN/THF) produced **3b** in 90% yield (*Table 2*, *Entry 2*). Similarly, radical cyclizations of 3-(1-benzofuran-2-yl)-3-oxopropanenitrile (**1c**) and 4,4-dimethyl-3-oxopentanenitrile (**1d**) with **2a** in the presence of CAN gave the corresponding dihydrofurans in high yield (*Entries 3* and *4*). Reactions of **1a** with styrene (**2b**) and (1*E*)-1-phenylprop-1-ene (**2c**) which are less reactive than **2a**, furnished **3e** (42%) and **3f** (75%) in moderate to good yield (*Entries 5* and *6*). Whereas the reaction of 2-phenylprop-1-ene (**2d**) with **1a** and MAH/AcOH produced **3h** in 25% yield, the same reaction with CAN resulted in 80% yield (*Entry 8*). The reactions of the 3-oxopropanenitriles **1b**, **1c**, and **1e** with **2d** gave remarkable results (*Entries 9–11*). These facts evidently demonstrate that CAN/THF is a method superior to MAH/AcOH. Radical cyclizations of **1a** and **1e** with sterically hindered alkene **2e** showed again that CAN/THF is more efficient (*Table 2*, *Entries 12* and *13*). Moreover, 3-oxopropanenitriles **1a** and **1d** and alkenes **2f** and **2g** with 4-F and 4-Me substituents, respectively, gave 4,5-dihydrofuran-3-carbonitriles in similarly high yields (*Entries 14* and *19*).

This method could also be employed for other 1,3-diketones. The reaction of 4-hydroxycoumarin (**4**) and **2d** with CAN/THF at 40–50° for 10 min gave 2-methyl-2-phenyl-4*H*-furo[3,2-*c*][1]benzopyran-4-one (**4a**) in 72% yield (*Scheme 2*). Ketone **4a** has been synthesized in lower yields in the presence of Ag/*Celite* (37% [11] and 46% [12]) as well as in the presence of CAN under different reaction conditions (62% [2c] and 70% [2k]). Moreover, the radical cyclization of ethyl 3-oxobutanoate (**5**) with **2d** under the same conditions (CAN/THF) gave ethyl 4,5-dihydro-2,5-dimethyl-5-phenylfuran-3-carboxylate (**5a**) in 79% yield. This compound has been obtained in the ionic liquid [bmim][BF_4]/CH_2Cl_2 1:9 as a solvent in the same yield but after 2 h (bmim = 1-butyl-9-methyl-1*H*-imidazolium) [2k]. A similar radical cyclization with 1,1-diphenyl-

Table 2. *Radical Cyclization of 3-Oxopropanenitriles and Alkenes with CAN/THF*



1a – 1e **2a – 2g** **3a – 3t**

Entry	Nitrile	R^1	Alkene	R^2	R^3	R^4	Product	Yield [%][a])	Yield [%][b]) MAH/AcOH
1	**1a**	Ph	**2a**	Ph	Ph	H	**3a**	97	65
2	**1b**	furan-2-yl	**2a**				**3b**	90	50
3	**1c**	1-benzofuran-2-yl	**2a**				**3c**	96	
4	**1d**	^{t}Bu	**2a**				**3d**	90	62
5	**1a**	Ph	**2b**	Ph	H	H	**3e**	42	12
6	**1a**	Ph	**2c**	Ph	H	Me	**3f**	75	
7	**1e**	2-thienyl	**2c**				**3g**	77	
8	**1a**	Ph	**2d**	Ph	Me	H	**3h**	80	25
9	**1b**	furan-2-yl	**2d**				**3i**	77	
10	**1c**	1-benzofuran-2-yl	**2d**				**3j**	81	
11	**1e**	2-thienyl	**2d**				**3k**	86	
12	**1a**	Ph	**2e**	Ph	Ph	Et	**3l**	83	63
13	**1e**	2-thienyl	**2e**				**3m**	80	44
14	**1a**	Ph	**2f**	4-FC_6H_4	4-FC_6H_4	H	**3n**	86	62
15	**1b**	furan-2-yl	**2f**				**3o**	82	
16	**1c**	1-benzofuran-2-yl	**2f**				**3p**	88	
17	**1e**	2-thienyl	**2f**				**3q**	85	
18	**1b**	furan-2-yl	**2g**	4-MeC_6H_4	4-MeC_6H_4	H	**3r**	82	
19	**1d**	^{t}Bu	**2g**				**3s**	80	
20	**1e**	2-thienyl	**2g**				**3t**	87	

[a]) Yields of isolated product based on the alkene. [b]) Yields taken from [10][4f].

ethylene (**2a**) produced **5b** in 81% yield, which has been obtained in 75% yield in ionic liquid [2k] and in 44% yield in MeCN by CAN [13].

Conclusions. – In this study, CAN was applied to the radical cyclizations of 3-oxopropanenitriles **1a**–**1e** with alkenes **2a**–**2g** for the first time. MeOH and MeCN, generally used for the reactions of CAN, either were not sufficiently effective or failed to form the products. An optimization study with ether solvents established that THF, Et_2O, and 1,4-dioxane are highly efficient in the reactions of CAN. Furthermore, 4,5-dihydrofuran-3-carbonitriles were obtained in higher yields with CAN than with MAH. The high efficiency of CAN/THF in radical cyclizations can be explained by the low solubility of CAN in THF that causes a stepwise release of Ce^{4+} ions into the reaction medium and thus prevents the formation of possible by-products.

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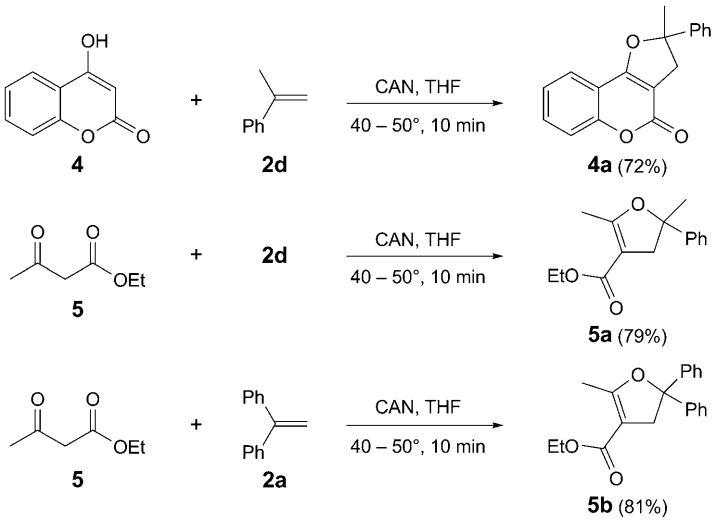
Scheme 2. *Radical Cyclization of* **4** *and* **5** *with Alkenes*



Experimental Part

General. All solvents were dried by standart methods. Column chromatography (CC): silica gel (SiO_2; 230–400 mesh; *Merck*). TLC: anal. aluminium plates coated with SiO_2 *60* $F_{254-366}$ (0.2 mm; *Merck*). M.p.: electrothermal melting point apparatus; uncorrected. IR Spectra: FT-IR *Matson-1000* instrument; KBr pellets; 400–4000 cm^{-1} range with 4 cm^{-1} resolution; $\tilde{\nu}$ in cm^{-1}. ^{1}H- and ^{13}C-NMR Spectra: *Mercury-400* high-performance digital FT-NMR insrument; in $CDCl_3$; δ in ppm rel. to Me_4Si as internal standard, *J* in Hz. LC/ESI-MS: *Waters-2695-Alliance-Micromass-ZQ* instrument; in *m*/*z* (rel. %).

4,5-Dihydrofuran-3-carbonitriles **3a**–**3t**. *General Procedure.* To a soln. of 3-oxopropanenitrile (1.2 mmol) and alkene (1 mmol) in THF (10 ml) under N_2, a mixture of CAN (3 mmol) and $NaHCO_3$ (3 mmol) was added at 40°. Then, the temp. was slowly increased to 60°. The reaction was completed when the orange color of CAN had disappeared (10–30 min) or when the alkene spot on TLC had completely vanished. H_2O was added to the soln., and the mixture was extracted with $CHCl_3$ (3 × 20 ml). The combined org. phase was dried (Na_2SO_4) and concentrated and the crude product purified by CC (SiO_2, 230–400 mesh) or prep. TLC (20 × 20 cm plates, 2 mm thickness, hexane/AcOEt 5 :1).

4,5-Dihydro-2,5,5-triphenylfuran-3-carbonitrile (**3a**): Yield 0.313 g (97%). Colorless solid. M.p. 134–136° (hexane/AcOEt). ^{1}H-NMR: 8.10 (*dd*, *J* = 7.0, 2.7, 2 arom. H); 7.50–7.28 (*m*, 13 arom. H); 3.78 (*s*, CH_2(4)).

2-(Furan-2-yl)-4,5-dihydro-5,5-diphenylfuran-3-carbonitrile (**3b**): Yield 0.282 g (90%). Pale yellow oil. ^{1}H-NMR: 7.63 (*d*, *J* = 1.6, 1 H); 7.40–7.30 (*m*, 12 arom. H); 7.11 (*d*, *J* = 3.5, 1 H); 6.56 (*dd*, *J* = 3.5, 1.6, 1 H); 3.73 (*s*, CH_2(4)).

2-(Benzofuran-2-yl)-4,5-dihydro-5,5-diphenylfuran-3-carbonitrile (**3c**): Yield 0.348 g (96%). Yellow solid. M.p. 165–167° (hexane/AcOEt). IR: 3061, 2200 (CN), 1648 (C=C), 1180 (C–O–C), 829, 750, 698. ^{1}H-NMR: 7.67 (*d*, *J* = 7.8, 1 H); 7.62 (*d*, *J* = 8.2, 1 H); 7.47–7.44 (*m*, 6 arom. H); 7.40–7.35 (*m*, 4 arom. H); 7.38–7.28 (*m*, 3 arom. H); 3.79 (*s*, CH_2(4)). ^{13}C-NMR: 157.0 (C(2)); 155.7; 144.9; 143.5; 128.8; 128.5; 127.5; 127.2; 125.9; 124.1; 122.5; 121.1; 116.2 (CN); 112.3; 110.3; 94.5; 81.2 (C(5)); 45.5 (C(4)). LC/ESI-MS: 364 (100, $[M+H]^+$). Anal. calc. for $C_{25}H_{17}NO_2$: C 82.63, H 4.72, N 3.85; found: C 82.86, H 4.37, N 4.05.

*2-(*tert*-Butyl)-4,5-dihydro-5,5-diphenylfuran-3-carbonitrile* (**3d**): Yield 0.273 g (90%). Yellow oil. ^{1}H-NMR: 7.40–7.48 (*m*, 10 arom. H); 3.58 (*s*, CH_2(4)); 1.36 (*s*, ^{t}Bu).

4,5-Dihydro-2,5-diphenylfuran-3-carbonitrile (**3e**): Yield 0.103 g (42%). Yellow oil. ^{1}H-NMR: 8.02 (*dd*, *J* = 8.0, 5.0, 2 arom. H); 7.48 – 7.36 (*m*, 8 arom. H); 5.83 (*dd*, *J* = 11.2, 8.4, H–C(5)); 3.53 (*dd*, *J* = 14.8, 10.8, H_a–C(4)); 3.10 (*dd*, *J* = 14.8, 8.4, H_b–C(4)).

4,5-Dihydro-4-methyl-2,5-diphenylfuran-3-carbonitrile (**3f**): Yield 0.195 g (75%). Yellow oil. IR: 3030, 2207 (CN), 1646 (C=C), 1232 (C–O–C), 758, 706. ^{1}H-NMR: 8.02 (*dd*, *J* = 8.0, 2.0, 2 arom. H); 7.50 – 7.36 (*m*, 8 arom. H); 5.25 (*d*, *J* = 8.8, H–C(5)); 3.37 (*dq*, *J* = 8.8, 6.8, H–C(4)); 1.44 (*d*, *J* = 6.8, Me). ^{13}C-NMR: 166.0 ((C(2)); 139.7; 131.7; 129.1; 129.0; 128.9; 128.1; 127.4; 125.9; 117.4 (CN); 91.8; 85.7 (C(5)); 47.9 (C(4)); 18.8 (Me). LC/ESI-MS: 262 (100, $[M+H]^+$). Anal. calc. for $C_{18}H_{15}NO$: C 82.73, H 5.79, N 5.36; found: C 82.42, H 5.76, N 5.53.

4,5-Dihydro-4-methyl-5-phenyl-2-(2-thienyl)furan-3-carbonitrile (**3g**): Yield 0.205 g (77%). Yellow oil. IR: 3026, 2207 (CN), 1650 (C=C), 1244 (C–O–C), 758, 702. ^{1}H-NMR: 7.90 (*dd*, *J* = 3.6, 0.8, 1 arom. H); 7.52 (*dd*, *J* = 5.2, 1.2, 1 arom. H); 7.42 – 7.36 (*m*, 5 arom. H); 7.15 (*dd*, *J* = 5.2, 4.4, 1 arom. H); 5.26 (*d*, *J* = 8.4, H–C(5)); 3.36 (*dq*, *J* = 8.4, 6.4, H–C(4)); 1.43 (*d*, *J* = 6.4, Me). ^{13}C-NMR: 161.4 (C(2)); 139.4; 130.3; 130.2; 130.1; 129.15; 129.1; 128.3; 126.0; 117.1 (CN); 92.5; 84.1 (C(5)); 47.7 (C(4)); 18.8 (Me). LC/ESI-MS: 268 (100, $[M+H]^+$). Anal. calc. for $C_{16}H_{13}NOS$: C 71.88, H 4.90, N 5.24, S 11.99; found: C 71.74, H 4.68, N 5.40, S 12.32.

4,5-Dihydro-5-methyl-2,5-diphenylfuran-3-carbonitrile (**3h**): Yield 0.209 g (80%). Yellow oil. ^{1}H-NMR: 8.05 (*dd*, *J* = 7.81, 1.95, 2 arom. H); 7.49 – 7.31 (*m*, 8 arom. H); 3.31 (*d*, *J* = 14.5, H_a–C(4)); 3.23 (*d*, *J* = 14.5, H_b–C(4)); 1.40 (*s*, Me).

4,5-Dihydro-5-methyl-5-phenyl[2,2′-bifuran]-3-carbonitrile (**3i**): Yield 0.193 g (77%). Yellow oil. IR: 3061, 2209 (CN), 1648 (C=C), 1180 (C–O–C), 758, 702. ^{1}H-NMR: 7.61 (*d*, *J* = 1.2, 1 arom. H); 7.39 – 7.32 (*m*, 5 arom. H); 7.06 (*d*, *J* = 3.6, 1 arom. H); 6.65 (*dd*, *J* = 3.6, 1.6, 1 arom. H); 3.26 (*d*, *J* = 14.4, H_a–C(4)); 3.19 (*d*, *J* = 14.8, H_b–C(4)); 1.08 (*s*, Me). ^{13}C-NMR: 156.9 (C(2)); 145.2; 144.7; 143.7; 128.6; 127.8; 124.1; 116.6 (CN); 113.9; 111.8; 91.1; 77.5 (C(5)); 45.2 (C(4)); 28.9 (Me). LC/ESI-MS: 252 (100, $[M+H]^+$). Anal. calc. for $C_{16}H_{13}NO_2$: C 76.48, H 5.21, N 5.57; found: C 76.76, H 5.01, N 5.64.

2-(1-Benzofuran-2-yl)-4,5-dihydro-5-methyl-5-phenylfuran-3-carbonitrile (**3j**): Yield 0.244 g (81%). Pale yellow solid. M.p. 104 – 106° (hexane/AcOEt). IR: 3082, 2198 (CN), 1619 (C=C), 1211 (C–O–C), 856, 760, 696. ^{1}H-NMR: 7.66 (*d*, *J* = 7.6, 1 arom. H); 7.61 (*d*, *J* = 8.0, 1 arom. H); 7.43 – 7.37 (*m*, 5 arom. H); 7.35 – 7.28 (*m*, 3 arom. H); 3.32 (*d*, *J* = 15.2, H_a–C(4)); 3.25 (*d*, *J* = 14.8, H_b–C(4)); 1.85 (*s*, Me). ^{13}C-NMR: 157.2 (C(2)); 155.6; 145.1; 144.8; 128.9; 128.1; 127.5; 127.1; 124.3; 124.0; 122.4; 116.5 (CN); 112.3; 110.2; 91.6; 80.7 (C(5)); 45.8 (C(4)); 29.1 (Me). LC/ESI-MS: 302 (100, $[M+H]^+$). Anal. calc. for $C_{20}H_{15}NO_2$: C 79.72, H 5.02, N 4.65; found: C 79.84, H 4.88, N 4.89.

4,5-Dihydro-5-methyl-5-phenyl-2-(2-thienyl)furan-3-carbonitrile (**3k**): Yield 0.229 g (86%). Yellow oil. IR: 3026, 2970, 2201 (CN), 1635 (C=C), 1180 (C–O–C), 764, 702. ^{1}H-NMR: 7.09 (*dd*, *J* = 4.0, 0.8, 1 arom. H); 7.50 (*dd*, *J* = 5.2, 0.8, 1 arom. H); 7.38 – 7.36 (*m*, 4 arom. H); 7.30 (*t*, *J* = 3.2, 1 arom. H); 7.14 (*dd*, *J* = 4.8, 4.0, 1 arom. H); 3.26 (*d*, *J* = 14.4, H_a–C(4)); 3.19 (*d*, *J* = 14.8, H_b–C(4)); 1.79 (*s*, Me). ^{13}C-NMR: 161.2 (C(2)); 145.1; 130.6; 130.1; 129.8; 128.9; 128.3; 128.0; 124.3; 117.6 (CN); 91.1; 77.2 (C(5)); 45.8 (C(4)); 28.8 (Me). LC/ESI-MS: 268 (100, $[M+H]^+$). Anal. calc. for $C_{16}H_{13}NOS$: C 71.88, H 4.90, N 5.24, S 11.99; found: C 71.61, H 4.76, N 5.17, S 12.13.

4-Ethyl-4,5-dihydro-2,5,5-triphenylfuran-3-carbonitrile (**3l**): Yield 0.291 g (83%). Pale yellow solid. M.p. 139 – 141° (hexane/AcOEt). ^{1}H-NMR: 8.26 (*dd*, *J* = 7.4, 1.7, 2 arom. H); 7.76 (*dd*, *J* = 7.5, 1.5, 2 arom. H); 7.68 – 7.66 (*m*, 3 arom. H); 7.56 (*tt*, *J* = 7.0, 1.6, 2 arom. H); 7.52 – 7.44 (*m*, 6 arom. H); 4.04 (*dd*, *J* = 7.7, 5.9, H–C(4)); 1.59 – 1.52 (*m*, MeCH_2); 1.14 (*t*, *J* = 7.4, *Me*CH_2).

4-Ethyl-4,5-dihydro-5,5-diphenyl-2-(2-thienyl)furan-3-carbonitrile (**3m**): Yield 0.257 g (72%). Yellow oil. ^{1}H-NMR: 7.88 (*d*, *J* = 3.8, 1 arom. H); 7.51 (*d*, *J* = 7.2, 1 arom. H); 7.48 (*d*, *J* = 5.0, 1 arom. H); 7.32 (*t*, *J* = 7.8, 1 arom. H); 7.26 – 7.19 (*m*, 7 arom. H); 7.09 (*t*, *J* = 4.8, 1 arom. H); 3.76 (*t*, *J* = 6.9, H–C(4)); 1.34 – 1.25 (*m*, MeCH_2); 0.89 (*t*, *J* = 7.4, *Me*CH_2).

5,5-Bis(4-fluorophenyl)-4,5-dihydro-2-phenylfuran-3-carbonitrile (**3n**): Yield 0.308 g (86%). Yellow oil. ^{1}H-NMR: 7.41 – 7.38 (*m*, 5 arom. H); 7.36 (*dd*, *J* = 9.0, 5.0, 4 arom. H); 7.12 (*t*, *J* = 8.4, 1 arom. H); 3.62 (*s*, CH_2(4)).

5,5-Bis(4-fluorophenyl)-4,5-dihydro[2,2′-bifuran]-3-carbonitrile (**3o**): Yield 0.286 g (82%). Yellow oil. IR: 3063, 2200 (CN), 1623 (C=C), 1253 (C–O–C), 829, 702. ^{1}H-NMR: 7.65 (*d*, *J* = 1.2, 1 arom. H); 7.40 – 7.36 (*dd*, *J* = 9.0, 5.0, 4 arom. H); 7.13 (*d*, *J* = 3.5, 1 arom. H); 7.08 (*t*, *J* = 8.6, 4 arom. H); 6.59 (*dd*,

$J = 3.5, 1.6, 1$ arom. H); 3.71 (*s*, $CH_2(4)$). ^{13}C-NMR: 163.6 – 161.4 (*d*, ^1J(C,F) = 246.9, C–F); 156.7 (C(2)); 145.8; 143.5; 139.2 (*d*, ^4J(C,F) = 3.2); 127.8 (*d*, ^3J(C,F) = 8.3); 116.2 (CN); 115.8 (*d*, ^2J(C,F) = 21.8); 114.5; 112.2; 93.4; 78.1 (C(5)); 45.3 (C(4)). LC/ESI-MS: 350 (100, $[M+H]^+$). Anal. calc. for $C_{21}H_{13}F_2NO_2$: C 72.20, H 3.75, N 4.01; found: C 72.44, H 3.52, N 4.30.

2-(1-Benzofuran-2-yl)-5,5-bis(4-fluorophenyl)-4,5-dihydrofuran-3-carbonitrile (**3p**): Yield 0.351 g (88%). Yellow solid. M.p. 104 – 106° (hexane/AcOEt). IR: 3059, 2200 (CN), 1643 (C=C), 1172 (C–O–C), 835, 754, 700. ^{1}H-NMR: 7.65 (*d*, *J* = 7.6, 1 arom. H); 7.59 (*dd*, *J* = 8.4, 0.8, 1 arom. H); 7.44 (*s*, 1 H); 7.41 – 7.36 (*m*, 5 arom. H); 7.29 (*t*, *J* = 7.6, 1 H); 7.06 (*t*, *J* = 8.4, 4 H); 3.73 (*s*, $CH_2(4)$). ^{13}C-NMR: 163.9 – 161.4 (*d*, ^1J(C,F) = 246.9, C–F); 156.8 (C(2)); 144.6; 139.1 (*d*, ^4J(C,F) = 3.1); 127.8 (*d*, ^3J(C,F) = 7.7); 127.4; 127.3; 124.1; 122.5; 115.8 (*d*, ^2J(C,F) = 21.3); 115.9 (CN); 112.3; 110.6; 93.6; 81.1 (C(5)); 45.6 (C(4)). LC/ESI-MS: 400 (100, $[M+H]^+$). Anal. calc. for $C_{25}H_{15}F_2NO_2$: C 75.18, H 3.79, N 3.51; found: C 75.52, H 3.66, N 3.42.

5,5-Bis(4-fluorophenyl)-4,5-dihydro-2-(2-thienyl)furan-3-carbonitrile (**3q**): Yield 0.310 g (85%). Yellow oil. IR: 3028, 2194 (CN), 1606 (C=C), 1257 (C–O–C), 835, 702. ^{1}H-NMR: 7.95 (*d*, *J* = 3.9, 1 H); 7.56 (*d*, *J* = 4.7, 1 H); 7.37 (*dd*, *J* = 9.0, 5.08, 4 H); 7.18 (*t*, *J* = 3.9, 1 H); 7.06 (*t*, *J* = 8.6, 4 H); 3.65 (*s*, $CH_2(4)$). ^{13}C-NMR: 163.8 – 161.4 (*d*, ^1J(C,F) = 246.8, C–F); 160.8 (C(2)); 139.3 (*d*, ^4J(C,F) = 3.2); 130.4; 130.2; 130.0; 128.5; 127.7 (*d*, ^3J(C,F) = 8.4); 116.9 (CN); 115.9 – 115.7 (*d*, ^2J(C,F) = 21.1); 93.1; 77.6 (C(5)); 45.6 (C(4)). LC/ESI-MS: 366 (100, $[M+H]^+$). Anal. calc. for $C_{21}H_{13}F_2NOS$: C 69.03, H 3.59, N 3.83, S 8.78; found: C 69.14, H 3.68, N 3.70, S 8.96.

4,5-Dihydro-5,5-bis(4-methylphenyl)[2,2′-bifuran]-3-carbonitrile (**3r**): Yield 0.280 g (82%). Yellow oil. IR: 3017, 2198 (CN), 1608 (C=C), 1255 (C–O–C), 835, 704. ^{1}H-NMR: 7.62 (*d*, *J* = 1.5, 1 H); 7.26 (*d*, *J* = 7.8, 4 H); 7.16 (*d*, *J* = 7.6, 1 H); 7.08 (*d*, *J* = 3.5, 1 H); 6.54 (*dd*, *J* = 3.5, 1.56, 1 H); 3.68 (*s*, $CH_2(4)$); 2.33 (*s*, 2 Me). ^{13}C-NMR: 157.0 (C(2)); 145.6; 143.9; 138.1; 129.4; 125.8; 116.7 (CN); 114.2; 112.1; 94.3; 78.1 (C(5)); 45.1 (C(4)); 21.2 (Me). LC/ESI-MS: 342 (100, $[M+H]^+$). Anal. calc. for $C_{23}H_{19}NO_2$: C 80.92, H 5.61, N 4.10; found: C 81.22, H 5.77, N 4.02.

*2-(*tert*-Butyl)-4,5-dihydro-5,5-bis(4-methylphenyl)furan-3-carbonitrile* (**3s**): Yield 0.265 g (80%). Yellow oil. IR: 3032, 2922, 2203 (CN), 1617 (C=C), 1111 (C–O–C), 827, 706. ^{1}H-NMR: 7.27 (*d*, *J* = 8.0, 4 H); 7.14 (*d*, *J* = 7.6, 4 H); 3.55 (*s*, $CH_2(4)$); 2.33 (*s*, 2 Me). ^{13}C-NMR: 177.7 (C(2)); 141.8; 137.8; 129.3; 125.6; 117.5 (CN); 92.3; 77.4 (C(5)); 64.0; 35.0 (C(4)); 28.3; 21.2 (Me). LC/ESI-MS: 332 (100, $[M+H]^+$). Anal. calc. for $C_{23}H_{25}NO$: C 83.34, H 7.60, N 4.23; found: C 83.54, H 7.46, N 4.36.

4,5-Dihydro-5,5-bis(4-methylphenyl)-2-(2-thienyl)furan-3-carbonitrile (**3t**): Yield 0.310 g (87%). Yellow oil. IR: 3078, 2205 (CN), 1618 (C=C), 1238 (C–O–C), 835, 696. ^{1}H-NMR: 7.92 (*dd*, *J* = 4.0, 0.8, 1 H); 7.52 (*dd*, *J* = 4.4, 0.4, 1 H); 7.27 (*d*, *J* = 8.0, 4 H); 7.15 (*d*, *J* = 7.6, 4 H); 3.70 (*s*, $CH_2(4)$); 2.32 (*s*, 3 Me). ^{13}C-NMR: 160.8 (C(2)); 140.8; 137.9; 130.2; 129.9; 129.7; 129.2; 128.1; 125.5; 117.1 (CN); 93.8; 77.4 (C(5)); 45.3 (C(4)); 21.0 (Me). LC/ESI-MS: 358 (100, $[M+H]^+$). Anal. calc. for $C_{23}H_{19}NOS$: C 77.28, H 5.36, N 3.92, S 8.97; found: C 77.38, H 5.11, N 4.11, S 9.12.

*2,3-Dihydro-2-methyl-2-phenyl-4*H*-furo[3,2-*c*][1]benzofuran-4-one* (**4a**): Yield 0.200 g (72%). Colorless solid. M.p. 114 – 116°. ^{1}H-NMR: 7.71 (*dd*, *J* = 6.3, 1.5, 1 H); 7.5 (*td*, *J* = 8.65, 1.59, 1 H); 7.37 – 7.26 (*m*, 7 arom. H); 3.35 (*d*, *J* = 15.4, H_a–C(3)); 3.26 (*d*, *J* = 15.1, H_b–C(3)); 1.83 (*s*, Me).

Ethyl 4,5-Dihydro-2,5-dimethyl-5-phenylfuran-3-carboxylate (**5a**): Yield 0.195 g (79%). Yellow oil. ^{1}H-NMR: 7.42 (*d*, *J* = 8.0, 2 H); 7.34 (*t*, *J* = 7.6, 2 H); 7.30 (*dd*, *J* = 8.0, 1.2, 1 H); 3.41 (*d*, *J* = 15.0, H_a–C(4)); 3.35 (*d*, *J* = 15.0, H_b–C(4)); 4.22 (*q*, *J* = 7.2, MeCH_2); 2.63 (*s*, Me); 1.34 (*t*, *J* = 7.2, MeCH_2).

Ethyl 4,5-Dihydro-2-methyl-5,5-diphenylfuran-3-carboxylate (**5b**): Yield 0.250 g (81%). Yellow oil. ^{1}H-NMR: 8.05 (*d*, *J* = 7.6, 1 H); 7.51 – 7.34 (*m*, 8 arom. H); 3.32 (*s*, $CH_2(4)$); 4.32 (*q*, *J* = 7.6, MeCH_2); 2.65 (*s*, Me); 1.35 (*t*, *J* = 7.6, MeCH_2).

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