DOI 10.1007/s10593-018-2206-1

Chemistry of Heterocyclic Compounds **2017**, *53*(12), 1286–1293

Copper(II) bromide-catalyzed conjugate addition of furans to α,β-unsaturated carbonyl compounds

Alexander A. Fadeev[1], Maxim G. Uchuskin[1,2], Igor V. Trushkov[2,3], Anton S. Makarov[1]*

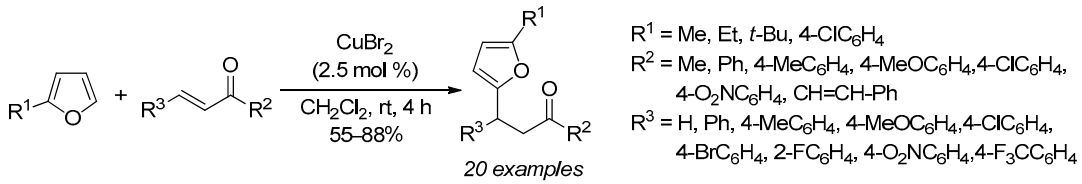
[1] *Perm State National Research University, 15 Bukirev St., Perm 614990, Russia; e-mail; antony.s.makarov@psu.ru*

[2] *RUDN University, 6 Miklukho-Maklaya St., Moscow 117198, Russia; e-mail: mu@psu.ru*

[3] *Dmitry Rogachev National Research Center of Pediatric Hematology, Oncology and Immunology, 1 Samory Mashela St., Moscow 117997, Russia; e-mail: itrushkov@mail.ru*

Translated from Khimiya Geterotsiklicheskikh Soedinenii, 2017, *53*(12), 1286–1293

Submitted September 28, 2017
Accepted November 14, 2017



A simple method for the synthesis of 2-(3-oxoalkyl)furan derivatives based on conjugate addition of 2-substituted furans to various α,β-unsaturated carbonyl compounds in the presence of copper(II) bromide as catalyst was developed.

Keywords: copper(II) bromide, furan, α,β-unsaturated carbonyl compounds, conjugate addition.

Significantly increasing interest toward furan derivatives has been noted over the recent decades. Apparently, it is stimulated by the existence of large number of natural compounds[1] and biologically active molecules containing a furan ring,[2] as well as motivated by the applications of furan derivatives for the synthesis of advanced materials.[3] The importance of this heterocycle is also raised by the availability of simple furans by the biomass processing.[4] Besides that, the diverse reactivity of furans, readily participating in dearomatization reactions with ring preservation or cleavage allows to use substituted furans in the synthesis of other types of organic compounds.[5] On the other hand, the pronounced lability of furan ring significantly limits the scope of methods available for its functionalization, to some degree creating obstacles to active development of furan chemistry.

The latest developments of methods for the synthesis of substituted furans have been guided by the principles of green chemistry,[6] focusing on atom economy and reducing the number of synthetic steps, in particular. Such emphasis allowed to minimize the formation of waste and thus to improve the environmental aspects of the chemical process. From this point of view, the most promising synthetic methods are based on catalytic C–H bond functionalization.[7] As a result, new approaches as well as modifications of classical methods that rely on electrophilic[8] and radical substitution[9] or reactions proceeding *via* the formation of transition metal complexes[10] are being developed.

The conjugate addition (Michael addition) is of particular importance among the methods for furan ring functionalization, that provides a versatile tool for effective and environmentally benign formation of chemical bonds.[11] The practical value of conjugate addition is based on the availability and broad structural diversity of electrophilic components that are able to react with furans. At the same time, conjugate addition reactions do not require preliminary introduction of additional functional groups into the structure of Michael acceptors. Finally, this reaction is not accompanied by the formation of any by-products.

A range of catalytic systems are currently known that can be used with various degrees of effectiveness for the preparation of conjugate addition products from furans and α,β-unsaturated ketones. The earliest examples of the discussed reaction relied on the use of mineral acids and

some hard Lewis acids as catalysts,[12] but such options are not currently favored due to the lability of furan ring in the presence of acids. On the other hand, catalysis by transition metal compounds has broader applicability in terms of searching for the optimal reaction conditions.[13] Various transition metal compounds are known to be effective catalysts for the conjugate addition of furans to α,β-unsaturated ketones.[14] However, the currently developed catalytic methods for performing this reaction are characterized by one substantial drawback – their effectiveness has been demonstrated only for a small number of substrates, which is insufficient for evaluating their range of practical applicability. Besides that, the need for costly catalysts requiring special storage conditions limits the economic significance of such methods. We have recently observed that copper(II) bromide is an effective catalyst for conjugate addition of furans to various chalcones.[15] Herein, we describe a simple method for the preparation of 2-(3-oxoalkyl)furan derivatives by conjugate addition reactions of 2-substituted furans to α,β-unsaturated carbonyl compounds in the presence of $CuBr_2$, a stable and inexpensive catalyst.

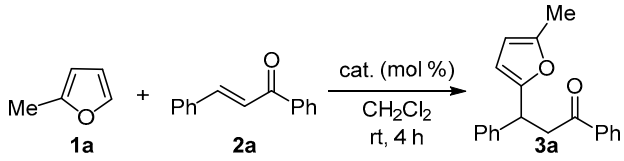
We studied readily available copper compounds as catalysts for Michael addition of furans to α,β-unsaturated carbonyl compounds.[16] The reaction conditions were optimized on a model reaction of 2-methylfuran (**1a**) with the unsubstituted chalcone **2a**. The examined copper(I) compounds (Table 1, entries 1–4) showed virtually no catalytic activity. Using a series of copper(II) compounds, such as CuO, $Cu(SO_4)_2 \cdot 5H_2O$, $Cu(NO_3)_2 \cdot 6H_2O$, $Cu(OAc)_2 \cdot H_2O$, and $Cu(OTf)_2$ (entries 5–9), the target product **3a** was formed in trace amounts. In a continuation of our search for an effective catalyst for the studied transformation among copper(II) salts, we found that $CuCl_2$ was moderately active as a catalyst: the yield of product **3a** in this case reached 48% (entry 10). The highest yield of the target product **3a** (79%) was achieved when the reaction was performed in the presence of 2.5 mol % $CuBr_2$ (entry 11). By varying the ratio of starting materials we found that the yield of product **3a** can be increased to 91% when the ratio of reagents **1a** and **2a** was equal to 1.5:1 (entry 12). It is important to note that increasing the catalyst load did not improve the yield of product **3a** (entry 13), while smaller amounts of the catalyst gave lower yields of product **3a** (entry 14). The use of alternative solvents such as ethyl acetate, 1,4-dioxane, DMF, ethanol, or toluene in this reaction did not improve the yield.

In order to verify the catalytic importance of copper ions in $CuBr_2$, instead of it acting only as a source of acid, we investigated whether the studied reaction can be catalyzed by the addition of HBr in the amount of 2.5 mol %, which would correspond to the amount of $CuBr_2$ used. Product **3a** in that case was formed only in 37% yield (Table 1, entry 17). It should be noted that the catalysts previously used for conjugate addition of furans to α,β-unsaturated carbonyl compounds, such as boron trifluoride etherate[12b] and sulfuric acid,[12c] were found to be ineffective in the studied reaction (entries 18, 19).

Thus, the optimum reaction conditions for conjugate addition of 2-methylfuran (**1a**) to the unsubstituted chalcone **2a** were achieved by stirring the reaction mixture in dichloromethane at room temperature for 4 h in the presence of 2.5 mol % $CuBr_2$ at 1.5:1 ratio of the starting materials **1a** and **2a**. Such reaction conditions allowed to perform the process on a preparative scale: the use of 0.5 mmol of the starting chalcone **2a** resulted in 84% isolated yield of product **3a**, while performing the reaction on 5 mmol-scale gave an 86% yield (Table 1, entry 12).

Next, we studied the scope of the reaction and the influence of different substituents in the structure of starting materials on the reaction outcome (Table 2). It was found that chalcones containing both electron-donating and electron-withdrawing substituents in the styrene moiety

Table 1. Optimization of reaction conditions for the addition of 2-methylfuran (**1a**) to chalcone **2a***



Entry	Catalyst	Amount of catalyst, mol %	Yield of product **3a****, %
1	Cu_2O	2.5	No conversion
2	CuCl	2.5	No conversion
3	CuBr	2.5	No conversion
4	CuI	2.5	No conversion
5	CuO	2.5	No conversion
6	$CuSO_4 \cdot 5H_2O$	2.5	Trace
7	$Cu(NO_3)_2 \cdot 6H_2O$	2.5	Trace
8	$Cu(OAc)_2 \cdot H_2O$	2.5	Trace
9	$Cu(OTf)_2$	2.5	Trace
10	$CuCl_2$	2.5	48
11	$CuBr_2$	2.5	79
12	**$CuBr_2$**	**2.5**	**91** (**1a**:**2a** = 1.5:1) **84** (**1a**:**2a** = 1.5:1)*** **86** (**1a**:**2a** = 1.5:1)*[4]
13	$CuBr_2$	5	91 (**1a**:**2a** = 1.5:1)
14	$CuBr_2$	1	76 (**1a**:**2a** = 1.5:1)
15	$CuBr_2$ (reaction time 3 h)	2.5	79
16	$CuBr_2$ (reaction time 6 h)	2.5	91
17	46% HBr/H_2O (reaction time 40 h)	2.5	37
18	$BF_3 \cdot Et_2O/Et_2O$	2.5	10
19	concd H_2SO_4	2.5	11

* The ratio of furan **1a** and ketone **2a** was 1:1.
** The yield was determined by GC/MS method using *n*-pentadecane as internal standard.
*** The yield of compound **3a** after column chromatography when using 0.5 mmol of chalcone **2a**.
*[4] The yield of compound **3a** after column chromatography when using 5 mmol of chalcone **2a**.

reacted with 2-methylfuran (**1a**), forming the corresponding products **3a**–**f** in 73–86% yields. The reaction of 2-methylfuran (**1a**) with chalcone **2c** containing a *para*-methoxy group required more forcing conditions, namely, heating in DCE at 40°C in the presence of 5 mol % $CuBr_2$. The product yields from conjugate addition of 2-methylfuran (**1a**) to chalcones containing electron-donating and electron-withdrawing substituents at the *para* position of benzoyl ring (compounds **2g**–**j**) were also comparable to the yield of product **3a** (70–81%). Thus, we did not observe a significant effect due to the substituents in the structure of monosubstituted chalcones on the target product yields.

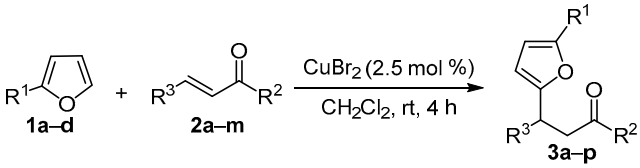
The reaction of 2-methylfuran (**1a**) with chalcone **2k** containing a nitro group at the *para* position of benzoyl ring and a methoxy group at the *para* position of styrene moiety led to the formation of adduct **3k** in 81% yield. On the other hand, product **3l** containing a nitro group at the *para* position of styrene moiety and a methoxy group at the *para* position of benzoyl ring was formed in 53% yield. In the latter case, a partial resinification of the reaction mixture was observed, while the conversion of the starting chalcone **2l** was incomplete even after 6 h. Increasing the reaction duration, the amount of starting furan, or the catalyst load only caused a higher degree of resinification instead of increasing the yield of target product **3l**.

The major product from the reaction of 2-methylfuran (**1a**) with dibenzylideneacetone **2m** was monoadduct **3m** having been isolated in 55% yield. Besides the main reaction product, we observed the formation of a mixture of compounds, apparently containing the bis-adduct of conjugate addition as a mixture of diastereomers, even though we could not isolate this compound as an individual sample.

The reaction of 2-ethylfuran (**1b**) with chalcone **2a** led to the formation of product **3n** in 88% yield. However, when the substituent at the C-2 atom of the starting furan was replaced with a *tert*-butyl group (compound **1c**) or a 4-chlorophenyl group (compound **1d**), the respective products were formed in low yields. Increasing the catalyst load up to 10 mol % did not improve the yield of products **3o**,**p** significantly, despite the complete conversion of the starting furans. Products **3o**,**p** were obtained as mixtures with the starting chalcone **2a** that were difficult to separate. No product from the reaction of chalcone **2a** with unsubstituted furan was observed; stirring the reaction mixture for 20 h only gave insignificant conversion of the starting chalcone.

When performing the reaction of 2-methylfuran (**1a**) with benzylideneacetone (**2n**), the target product **3q** was obtained in 63% yield (Table 3). A comparable yield of the Michael adduct **3s** was also observed in the case of methyl vinyl ketone (**2p**). The moderate yields of the target products **3q**,**s** in these cases were explained by the occurrence of side reactions, but we were unable to isolate and characterize any by-products. It is important to note that the reaction of 2-methylfuran (**1a**) with 4-(4-chlorophenyl)but-3-en-2-one (**2o**), in contrast to the reaction with benzylideneacetone (**2n**), provided a high yield of the

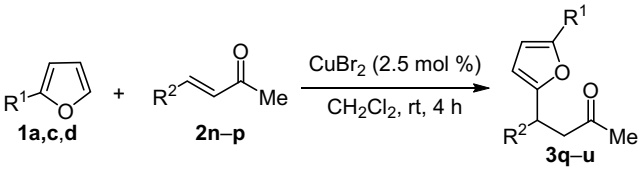
Table 2. The range of applicability for the conjugate addition of furans **1** to unsaturated ketones **2***



Furan	R^1	Ketone	R^2	R^3	Product	Yield**, %
1a	Me	**2a**	Ph	Ph	**3a**	84
1a	Me	**2b**	Ph	4-MeC_6H_4	**3b**	73
1a	Me	**2c**	Ph	4-$MeOC_6H_4$	**3c**	75***
1a	Me	**2d**	Ph	4-BrC_6H_4	**3d**	85
1a	Me	**2e**	Ph	4-$F_3CC_6H_4$	**3e**	86
1a	Me	**2f**	Ph	2-FC_6H_4	**3f**	77
1a	Me	**2g**	4-MeC_6H_4	Ph	**3g**	70
1a	Me	**2h**	4-$MeOC_6H_4$	Ph	**3h**	71
1a	Me	**2i**	4-ClC_6H_4	Ph	**3i**	79
1a	Me	**2j**	4-$O_2NC_6H_4$	Ph	**3j**	81
1a	Me	**2k**	4-$O_2NC_6H_4$	4-$MeOC_6H_4$	**3k**	81***
1a	Me	**2l**	4-$MeOC_6H_4$	4-$O_2NC_6H_4$	**3l**	53*[4]
1a	Me	**2m**	PhCH=CH	Ph	**3m**	55
1b	Et	**2a**	Ph	Ph	**3n**	88
1c	*t*-Bu	**2a**	Ph	Ph	**3o**	10*[5]
1d	4-ClC_6H_4	**2a**	Ph	Ph	**3p**	40*[5]

* Scale of reaction – 0.5 mmol, ratio of reagents **1**:**2** = 1.5:1.
** Yield after column chromatography step.
*** In DCE at 40°C in the presence of 5 mol % $CuBr_2$, reaction time 5 h.
*[4] Reaction time 6 h.
*[5] The catalyst was 10 % $CuBr_2$. The yield was determined by ^{1}H NMR spectroscopy using CH_2Br_2 as internal standard.

Table 3. The yields of conjugate addition products **3q**–**u***



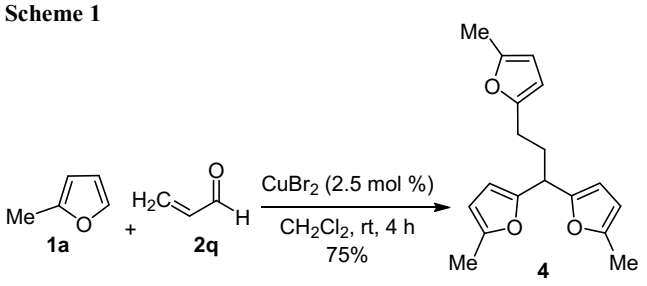
Furan	R^1	Ketone	R^2	Product	Yield**, %
1a	Me	**2n**	Ph	**3q**	63***
1a	Me	**2o**	4-ClC_6H_4	**3r**	88
1a	Me	**2p**	H	**3s**	65***
1c	*t*-Bu	**2p**	H	**3t**	81
1d	4-ClC_6H_4	**2p**	H	**3u**	84

* Reaction scale – 0.5 mmol, ratio of reagents **1**:**2** = 1:1.
** Yield after column chromatography.
*** Reaction time 2 h. A mixture of by-products was formed besides the target furanylbutanone **3**.

respective product. Remarkably, the reactions of methyl vinyl ketone **2p** with furans **1c**,**d** led to the formation of the respective products in yields above 80%.

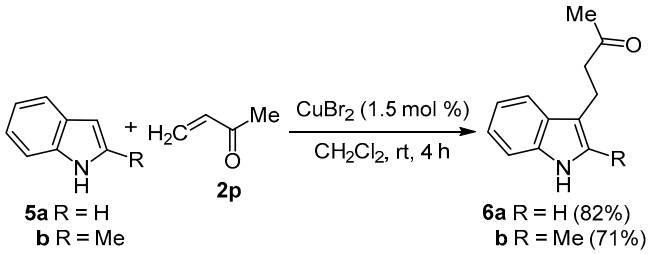
The reaction of 2-methylfuran (**1a**) with acrolein (**2q**) in the presence of $CuBr_2$ gave compound **4**, which was formed by condensation of the conjugate addition product with two additional molecules of 2-methylfuran (**1a**). This result can be explained by the stronger electrophilic properties of aldehyde carbonyl group compared to analogous ketones (Scheme 1).[17] The optimization of this reaction showed that the highest yield of compound **4** (75%) was achieved by using 5 equiv of 2-methylfuran (**1a**) relative to 1 equiv of acrolein. Still, the reaction mixture contained multiple unidentified minor products besides compound **4**.

Scheme 1



The developed catalytic conditions can be applied also for the functionalization of other electron-rich heterocyclic systems. Thus, indole (**5a**) and 2-methylindole (**5b**) participated in conjugate addition reactions with methyl vinyl ketone (**2p**), resulting in the formation of 4-(indol-3-yl)butan-2-ones **6a**,**b** in 82 and 71% yields, respectively (Scheme 2). It is necessary to note that 1.5 mol % of catalyst was sufficient for achieving this transformation.

Scheme 2



Obviously, $CuBr_2$ acted as a Lewis acid in this process and the studied reaction proceeded according to the well-known conjugate addition mechanism.[18]

Thus, we have developed a simple method for the synthesis of 2-(3-oxoalkyl)furan derivatives by conjugate addition of 2-substituted furans to α,β-unsaturated carbonyl compounds in the presence of $CuBr_2$. The method is characterized by low catalyst loads, mild reaction conditions, high yields of the target products, and broad scope. It was shown that the developed method can be used for functionalization of other electron-rich heterocyclic compounds.

Experimental

^1H and ^{13}C NMR spectra were acquired on a Bruker Avance III HD 400 spectrometer (400 and 100 MHz, respectively) at room temperature in DMSO-d_6 (compound **6b**) or $CDCl_3$ (the rest of the compounds). The chemical shifts were measured relative to the residual solvent signals (for ^1H nuclei: $CDCl_3$ – 7.26 ppm, DMSO-d_6 – 2.50 ppm; for ^{13}C nuclei: $CDCl_3$ – 77.16 ppm, DMSO-d_6 – 39.52 ppm). High-resolution mass spectra were recorded on a Bruker microTOF-Q ESI-TOF mass spectrometer. Analytical gas chromatography was performed on an Agilent 5977A GC/MSD instrument. Melting points were determined on a Stuart SMP 30 apparatus. TLC analyses were performed on Sorbfil plates. The reaction mixtures were purified by using Macherey Nagel silica gel (40–63 μm).

Compounds **1c**,[19a] **1d**,[19b] **2b–i**,[19c] **2j**,**l**,**m**,[19d] and **2o**[19e] were obtained according to published procedures, with the physicochemical characteristics of the obtained compounds matching the literature data. Compounds **1a**,**b**, **2a**,**p**,**q** were commercially available.

Preparation of compounds 3a,b,d–j,l–p (General method). $CuBr_2$ (2.8 mg, 2.5 mol %) was added to a solution of ketone **2** (0.5 mmol) and furan **1** (0.75 mmol) in dichloromethane (1.25 ml). The reaction mixture was stirred for 4 h at room temperature while controlling the reaction progress by TLC. Upon comletion, the mixture was concentrated at reduced pressure. The product was isolated by column chromatography (eluent petroleum ether – CH_2Cl_2, gradient from 19:1 to 1:1). Products **3o**,**p** were not isolated as individual compounds.

Preparation of compounds 3c,k (General method). $CuBr_2$ (5.6 mg, 5 mol %) was added to a solution of ketone **2** (0.5 mmol) and furan **1a** (68 μl, 0.75 mmol) in 1,2-dichloroethane (1.25 ml). The reaction mixture was stirred for 5 h at 40°C while controlling the reaction progress by TLC. Upon comletion, the mixture was concentrated at reduced pressure. The product was isolated by column chromatography (eluent petroleum ether – CH_2Cl_2, gradient from 19:1 to 1:1).

Preparation of compounds 3q–u (General method). $CuBr_2$ (2.8 mg, 2.5 mol %) was added to a solution of ketone **2** (0.5 mmol) and furan **1** (0.5 mmol) in dichloromethane (1.25 ml). The reaction mixture was stirred for 4 h at room temperature while controlling the reaction progress by TLC. Upon comletion, the mixture was concentrated at reduced pressure. The product was isolated by column chromatography (eluent petroleum ether – CH_2Cl_2, gradient from 19:1 to 1:1).

3-(5-Methylfuran-2-yl)-1,3-diphenylpropan-1-one (3a). Yield 122 mg (84%), light-yellow oil. ^1H NMR spectrum, δ, ppm (*J*, Hz): 2.23 (3H, s, CH_3); 3.54 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 3.80 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 4.80 (1H, t, ^3J = 7.2, CH); 5.85 (1H, d, ^3J = 2.8, H furan); 5.91 (1H, d, ^3J = 2.8, H furan); 7.20–7.25 (1H, m, H Ph); 7.28–7.36 (4H, m, H Ph); 7.42–7.47 (2H, m, H Ph); 7.53–7.57 (1H, m, H Ph); 7.94–7.96 (2H, m, H Ph). ^{13}C NMR spectrum, δ, ppm: 13.6; 40.6; 43.9; 106.1; 106.6; 126.8; 128.0 (2C); 128.2 (2C); 128.6 (2C); 128.7 (2C); 133.1;

137.3; 142.4; 151.2; 155.0; 197.8. Found, *m/z*: 291.1379 $[M+H]^+$. $C_{20}H_{19}O_2$. Calculated, *m/z*: 291.1380.

3-(5-Methylfuran-2-yl)-3-(4-methylphenyl)-1-phenylpropan-1-one (3b). Yield 111 mg (73%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.22 (3H, s, CH_3); 2.32 (3H, s, CH_3); 3.52 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 3.78 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 4.76 (1H, t, ^3J = 7.2, CH); 5.83 (1H, br. s, H furan); 5.90 (1H, br. s, H furan); 7.11–7.18 (2H, m, H Ar); 7.23–7.26 (2H, m, H Ph); 7.42–7.48 (2H, m, H Ar); 7.53–7.57 (1H, m, H Ph); 7.94–7.96 (2H, m, H Ph). ^{13}C NMR spectrum, δ, ppm: 13.6, 21.1; 40.3, 44.0; 106.1; 106.5; 127.9 (2C); 128.2 (2C); 128.7 (2C); 129.3 (2C); 133.1; 136.3; 137.3; 139.4; 151.1; 155.3; 197.9. Found, *m/z*: 305.1544 $[M+H]^+$. $C_{21}H_{21}O_2$. Calculated, *m/z*: 305.1536.

3-(4-Methoxyphenyl)-3-(5-methylfuran-2-yl)-1-phenylpropan-1-one (3c). Yield 120 mg (75%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.22 (3H, s, CH_3); 3.51 (1H, dd, ^2J = 16.8, ^3J = 7.5, CH_2); 3.75 (1H, dd, ^2J = 16.8, ^3J = 7.5, CH_2); 3.77 (3H, s, OCH_3); 4.73 (1H, t, ^3J = 7.5, CH); 5.84 (1H, br. s, H furan); 5.88 (1H, br. s, H furan); 6.84 (2H, d, *J* = 8.0, H Ar); 7.24 (2H, d, *J* = 8.0, H Ar); 7.41–7.47 (2H, m, H Ph); 7.52–7.58 (1H, m, H Ph); 7.93–7.95 (2H, m, H Ph). ^{13}C NMR spectrum, δ, ppm: 13.7; 39.8; 44.0; 55.3; 106.1; 106.4; 114.1 (2C); 128.2 (2C); 128.7 (2C); 129.0 (2C); 133.1; 134.4; 137.2; 151.1; 155.4; 158.5; 198.0. Found, *m/z*: 321.1494 $[M+H]^+$. $C_{21}H_{21}O_3$. Calculated, *m/z*: 321.1485.

3-(4-Bromophenyl)-3-(5-methylfuran-2-yl)-1-phenylpropan-1-one (3d). Yield 157 mg (85%), orange oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.24 (3H, s, CH_3); 3.55 (1H, dd, ^2J = 17.2, ^3J = 7.7, CH_2); 3.78 (1H, dd, ^2J = 17.2, ^3J = 7.7, CH_2); 4.78 (1H, t, ^3J = 7.7, CH); 5.87 (1H, br. s, H furan); 5.93 (1H, br. s, H furan); 7.21–7.25 (2H, m, H Ar); 7.39–7.49 (4H, m, H Ph and Ar); 7.53–7.58 (1H, m, H Ph); 7.95–7.97 (2H, m, H Ph). ^{13}C NMR spectrum, δ, ppm: 13.6; 39.9; 43.5; 106.1; 106.7; 120.6; 128.1 (2C); 128.7 (2C); 129.8 (2C); 131.6 (2C); 133.2; 136.9; 141.3; 151.3; 154.3; 197.3. Found, *m/z*: 369.0501 $[M+H]^+$. $C_{20}H_{18}BrO_2$. Calculated, *m/z*: 369.0485.

3-(5-Methylfuran-2-yl)-1-phenyl-3-[4-(trifluoromethyl)-phenyl]propan-1-one (3e). Yield 154 mg (86%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.24 (3H, s, CH_3); 3.58 (1H, dd, ^2J = 17.3, ^3J = 7.8, CH_2); 3.80 (1H, dd, ^2J = 17.3, ^3J = 7.8, CH_2); 4.86 (1H, t, ^3J = 7.8, CH); 5.86 (1H, br. s, H furan); 5.93 (1H, br. s, H furan); 7.42–7.48 (4H, m, H Ar); 7.54–7.57 (3H, m, H Ar); 7.94–7.96 (2H, m, H Ar). ^{13}C NMR spectrum, δ, ppm (*J*, Hz): 13.6; 40.4; 43.5; 106.3; 107.0; 124.4 (q, $^1J_{CF}$ = 271.9), 125.6 (q, $^3J_{CF}$ = 3.7, 2C); 128.2 (2C); 128.5 (2C); 128.8 (2C); 129.2 (q, $^2J_{CF}$ = 32.4); 133.4; 137.0; 146.5; 151.6; 154.1; 197.2. Found, *m/z*: 359.1254 $[M+H]^+$. $C_{21}H_{18}F_3O_2$. Calculated, *m/z*: 359.1253.

3-(2-Fluorophenyl)-3-(5-methylfuran-2-yl)-1-phenylpropan-1-one (3f). Yield 119 mg (77%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.25 (3H, s, CH_3); 3.63 (1H, dd, ^2J = 17.1, ^3J = 7.1, CH_2); 3.85 (1H, dd, ^2J = 17.1, ^3J = 7.1, CH_2); 5.14 (1H, t, ^3J = 7.1, CH); 5.89 (1H, br. s, H furan); 5.98 (1H, br. s, H furan); 7.05–7.14 (2H, m, H Ar); 7.19–7.26 (1H, m, H Ar); 7.30–7.36 (1H, m, H Ar); 7.44–7.50 (2H, m, H Ar); 7.58–7.60 (1H, m, H Ar); 7.99–8.01 (2H, m, H Ar). ^{13}C NMR spectrum, δ, ppm (*J*, Hz): 13.5; 34.2 (d, $^3J_{CF}$ = 2.7); 42.5 (d, $^4J_{CF}$ = 1.5); 106.2; 106.9; 115.7 (d, $^2J_{CF}$ = 22.4); 124.2 (d, $^4J_{CF}$ = 3.5); 128.1 (2C); 128.4 (d, $^3J_{CF}$ = 8.3); 128.6 (2C); 129.2 (d, $^2J_{CF}$ = 14.0); 129.6 (d, $^3J_{CF}$ = 4.3); 133.1; 137.0; 151.2; 153.6; 160.7 (d, $^1J_{CF}$ = 246.4); 197.4. Found, *m/z*: 309.1274 $[M+H]^+$. $C_{20}H_{18}FO_2$. Calculated, *m/z*: 309.1285.

3-(5-Methylfuran-2-yl)-1-(4-methylphenyl)-3-phenylpropan-1-one (3g). Yield 106 mg (70%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.24 (3H, s, CH_3); 2.42 (3H, s, CH_3); 3.52 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 3.77 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 4.79 (1H, t, ^3J = 7.2, CH); 5.85 (1H, br. s, H furan); 5.91 (1H, br. s, H furan); 7.20–7.36 (7H, m, H Ar); 7.86–7.88 (2H, m, H Ar); ^{13}C NMR spectrum, δ, ppm: 13.7, 21.7; 40.6, 43.7; 106.1; 106.5; 126.8; 128.0 (2C); 128.4 (2C); 128.6 (2C); 129.4 (2C); 134.7; 142.5; 144.0; 151.2; 155.1; 197.4. Found, *m/z*: 305.1543 $[M+H]^+$. $C_{21}H_{21}O_2$. Calculated, *m/z*: 305.1536.

1-(4-Methoxyphenyl)-3-(5-methylfuran-2-yl)-3-phenylpropan-1-one (3h). Yield 114 mg (71%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.24 (3H, s, CH_3); 3.49 (1H, dd, ^2J = 16.7, ^3J = 7.2, CH_2); 3.75 (1H, dd, ^2J = 16.7, ^3J = 7.2, CH_2); 3.88 (3H, s, OCH_3); 4.79 (1H, t, ^3J = 7.2, CH); 5.85 (1H, br. s, H furan); 5.91 (1H, br. s, H furan); 6.94 (2H, d, *J* = 8.8, H Ar); 7.19–7.25 (1H, m, H Ph); 7.27–7.35 (4H, m, H Ph); 7.95 (2H, d, *J* = 8.8, H Ar). ^{13}C NMR spectrum, δ, ppm: 13.7; 40.7; 43.5; 55.6; 106.1; 106.5; 113.8 (2C); 126.8; 128.0 (2C); 128.6 (2C); 130.3; 130.5 (2C); 142.6; 151.1; 155.2; 163.6; 196.3. Found, *m/z*: 321.1478 $[M+H]^+$. $C_{21}H_{21}O_3$. Calculated, *m/z*: 321.1485.

1-(4-Chlorophenyl)-3-(5-methylfuran-2-yl)-3-phenylpropan-1-one (3i). Yield 128 mg (79%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.22 (3H, s, CH_3); 3.50 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 3.75 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 4.77 (1H, t, ^3J = 7.2, CH); 5.85 (1H, br. s, H furan); 5.89 (1H, br. s, H furan); 7.19–7.25 (1H, m, H Ph); 7.28–7.34 (4H, m, H Ph); 7.41 (2H, d, *J* = 8.0, H Ar); 7.87 (2H, d, *J* = 8.0, H Ar). ^{13}C NMR spectrum, δ, ppm: 13.6; 40.7; 43.8; 106.2; 106.7; 126.9; 128.0 (2C); 128.7 (2C); 129.0 (2C); 129.6 (2C); 135.6; 139.6; 142.2; 151.2; 154.8; 196.6. Found, *m/z*: 325.0998 $[M+H]^+$. $C_{20}H_{18}ClO_2$. Calculated, *m/z*: 325.0990.

3-(5-Methylfuran-2-yl)-1-(4-nitrophenyl)-3-phenylpropan-1-one (3j). Yield 136 mg (81%), yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.21 (3H, s, CH_3); 3.55 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 3.82 (1H, dd, ^2J = 16.9, ^3J = 7.2, CH_2); 4.74 (1H, t, ^3J = 7.2, CH); 5.84 (1H, br. s, H furan); 5.88 (1H, br. s, H furan); 7.20–7.25 (1H, m, H Ph); 7.27–7.33 (4H, m, H Ph); 8.05 (2H, d, ^3J = 8.7, H Ar); 8.28 (2H, d, ^3J = 8.7, H Ar). ^{13}C NMR spectrum, δ, ppm: 13.7; 40.7; 44.4; 106.2; 106.9; 123.9 (2C); 127.1; 127.9 (2C); 128.8 (2C); 129.2 (2C); 141.6; 141.8; 150.5; 151.4; 154.4; 196.6. Found, *m/z*: 336.1236 $[M+H]^+$. $C_{20}H_{18}NO_4$. Calculated, *m/z* 336.1230.

3-(4-Methoxyphenyl)-3-(5-methylfuran-2-yl)-1-(4-nitrophenyl)propan-1-one (3k). Yield 148 mg (81%), orange oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.21 (3H, s, CH_3); 3.53 (1H, dd, ^2J = 16.9, ^3J = 7.5, CH_2); 3.77 (3H, s,

OCH_3); 3.79 (1H, dd, ^2J = 16.9, ^3J = 7.5, CH_2); 4.69 (1H, t, ^3J = 7.5, CH); 5.83–5.86 (2H, m, H furan); 6.83 (2H, d, ^3J = 8.6, H Ar); 7.23 (2H, d, ^3J = 8.6, H Ar); 8.05 (2H, d, ^3J = 8.8, H Ar); 8.27 (2H, d, ^3J = 8.8, H Ar). ^{13}C NMR spectrum, δ, ppm: 13.6; 39.9; 44.5; 55.3; 106.2; 106.7; 114.2 (2C); 123.9 (2C); 128.9 (2C); 129.2 (2C); 133.8; 141.6; 150.4; 151.3; 154.8; 158.7; 196.7. Found, *m*/*z*: 366.1351 $[M+H]^+$. $C_{21}H_{20}NO_5$. Calculated, *m*/*z*: 366.1336.

1-(4-Methoxyphenyl)-3-(5-methylfuran-2-yl)-3-(4-nitrophenyl)propan-1-one (3l). Yield 97 mg (53%), orange oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.21 (3H, s, CH_3); 3.56 (1H, dd, ^2J = 17.2, ^3J = 7.5, CH_2); 3.73 (1H, dd, ^2J = 17.2, ^3J = 7.5, CH_2); 3.84 (3H, s, OCH_3); 4.86 (1H, t, ^3J = 7.5, CH); 5.86 (1H, br. s, H furan); 5.96 (1H, br. s, H furan); 6.91 (2H, d, ^3J = 8.8, H Ar); 7.47 (2H, d, ^3J = 8.7, H Ar); 7.91 (2H, d, ^3J = 8.8, H Ar); 8.11 (2H, d, *J* = 8.7, H Ar). ^{13}C NMR spectrum, δ, ppm: 13.6; 40.3; 42.7; 55.5; 106.3; 107.1; 113.9 (2C); 123.8 (2C); 129.0 (2C); 129.7; 130.4 (2C); 146.8; 150.0; 151.8; 153.4; 163.8; 195.3. Found, *m*/*z*: 366.1326 $[M+H]^+$. $C_{21}H_{20}NO_5$. Calculated, *m*/*z* 366.1336.

(*E*)-5-(5-Methylfuran-2-yl)-1,5-diphenylpent-1-en-3-one (3m). Yield 87 mg (55%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.25 (3H, s, CH_3); 3.24 (1H, dd, ^2J = 16.2, ^3J = 7.3, CH_2); 3.48 (1H, dd, ^2J = 16.2, ^3J = 7.3, CH_2); 4.69 (1H, t, ^3J = 7.3, CH); 5.87 (1H, br. s, H furan); 5.93 (1H, br. s, H furan); 6.71 (1H, d, *J* = 16.2, CH); 7.22–7.33 (5H, m, H Ph); 7.40–7.41 (3H, m, H Ph); 7.52–7.56 (3H, m, CH and H Ph). ^{13}C NMR spectrum, δ, ppm: 13.7; 40.9; 46.1; 106.2; 106.7; 126.5; 126.9; 128.0 (2C); 128.4 (2C); 128.7 (2C); 129.1 (2C); 130.6; 134.7; 142.4; 142.9; 151.2; 155.5; 197.8. Found, *m*/*z*: 317.1537 $[M+H]^+$. $C_{22}H_{21}O_2$. Calculated, *m*/*z*: 317.1536.

3-(5-Ethylfuran-2-yl)-1,3-diphenylpropan-1-one (3n). Yield 134 mg (88%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.21 (3H, t, ^3J = 7.5, CH_3); 2.61 (2H, q, ^3J = 7.5, CH_2); 3.56 (1H, dd, ^2J = 16.8, ^3J = 7.2, CH_2); 3.84 (1H, dd, ^2J = 16.8, ^3J = 7.2, CH_2); 4.85 (1H, t, ^3J = 7.2, CH); 5.88 (1H, d, ^3J = 2.8, H furan); 5.93 (1H, d, ^3J = 2.8, H furan); 7.21–7.26 (1H, m, H Ph); 7.30–7.39 (4H, m, H Ph); 7.42–7.48 (2H, m, H Ph); 7.52–7.57 (1H, m, H Ph); 7.97–7.99 (2H, m, H Ph). ^{13}C NMR spectrum, δ, ppm: 12.1; 21.4; 40.7; 43.9; 104.5; 106.4; 126.8; 128.0 (2C); 128.2 (2C); 128.6 (2C); 128.7 (2C) 133.1; 137.3; 142.4; 154.9; 156.9; 197.8. Found, *m*/*z*: 305.1549 $[M+H]^+$. $C_{21}H_{21}O_2$. Calculated, *m*/*z*: 305.1536.

4-(5-Methylfuran-2-yl)-4-phenylbutan-2-one (3q).[20] Yield 72 mg (63%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.11 (3H, s, CH_3); 2.26 (3H, s, CH_3); 3.01 (1H, dd, ^2J = 16.5, ^3J = 7.4, CH_2); 3.23 (1H, dd, ^2J = 16.5, ^3J = 7.4, CH_2); 4.58 (1H, t, ^3J = 7.4, CH); 5.88–5.90 (2H, m, H furan); 7.19–7.24 (1H, m, H Ph); 7.25–7.35 (4H, m, H Ph). ^{13}C NMR spectrum, δ, ppm: 13.6; 30.4; 40.6; 48.7; 106.1; 106.5; 126.9; 127.9 (2C); 128.6 (2C); 142.1; 151.2; 154.8; 206.2. Found, *m*/*z*: 229.1221 $[M+H]^+$. $C_{15}H_{17}O_2$. Calculated, *m*/*z*: 229.1223.

4-(4-Chlorophenyl)-4-(5-methylfuran-2-yl)butan-2-one (3r). Yield 115 mg (88%), orange oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.31 (3H, d, ^3J = 6.9, CH_3); 2.22 (3H, s, CH_3); 3.01 (1H, dd, ^2J = 16.3, *J* = 5.5, CH_2); 3.36 (1H, dd, ^2J = 16.3, ^3J = 5.5, CH_2); 3.45–3.56 (1H, m, CH); 5.82 (1H, br. s, H furan); 5.88 (1H, br. s, H furan); 7.41 (2H, d, ^3J = 8.8, H Ar); 7.88 (2H, d, ^3J = 8.8, H Ar). ^{13}C NMR spectrum, δ, ppm: 13.5; 19.1; 29.6; 44.6; 104.7; 105.9; 129.0 (2C); 129.7 (2C); 135.8; 139.5; 150.6; 157.3; 197.7. Found, *m*/*z*: 263.0842 $[M+H]^+$. $C_{15}H_{16}ClO_2$. Calculated, *m*/*z*: 263.0833.

4-(5-Methylfuran-2-yl)butan-2-one (3s).[21] Yield 49 mg (65%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.13 (3H, s, CH_3); 2.21 (3H, s, CH_3); 2.73 (2H, t, ^3J = 7.2, CH_2); 2.83 (2H, t, ^3J = 7.2, CH_2); 5.81–5.83 (2H, m, H furan). ^{13}C NMR spectrum, δ, ppm: 13.5; 22.3; 29.9; 41.9; 105.8; 106.0; 150.6; 152.7; 207.4. Found, *m*/*z*: 153.0914 $[M+H]^+$. $C_9H_{13}O_2$. Calculated, *m*/*z*: 153.0910.

4-(5-*tert*-Butylfuran-2-yl)butan-2-one (3t). Yield 79 mg (81%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.25 (9H, s, $C(CH_3)_3$); 2.15 (3H, s, CH_3); 2.75 (2H, t, ^3J = 7.4, CH_2); 2.88 (2H, t, ^3J = 7.4, CH_2); 5.80–5.84 (2H, m, H furan). ^{13}C NMR spectrum, δ, ppm: 22.7; 29.2 (3C); 30.0; 32.7; 42.0; 102.3; 105.4; 152.4; 163.1; 207.6. Found, *m*/*z*: 195.1388 $[M+H]^+$. $C_{12}H_{19}O_2$. Calculated, *m*/*z*: 195.1380.

4-[5-(4-Chlorophenyl)furan-2-yl]butan-2-one (3u). Yield 104 mg (84%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.19 (3H, s, CH_3); 2.83 (2H, t, ^3J = 7.2, CH_2); 2.98 (2H, t, ^3J = 7.2, CH_2); 6.08 (1H, br. s, H furan); 6.52 (1H, br. s, H furan); 7.32 (2H, d, ^3J = 8.1, H Ar); 7.53 (2H, d, ^3J = 8.1, H Ar). ^{13}C NMR spectrum, δ, ppm: 22.6; 30.0; 41.9; 106.4; 107.8; 124.8 (2C); 129.0 (2C); 129.7; 132.7; 151.7; 154.9; 207.0. Found, *m*/*z*: 249.0682 $[M+H]^+$. $C_{14}H_{14}ClO_2$. Calculated, *m*/*z*: 249.0677.

2,2',2''-Propane-1,1,3-triyltris(5-methylfuran) (4).[17a] $CuBr_2$ (2.8 mg, 2.5 mol %) was added to a solution of acrolein (**2q**) (33 μl, 0.5 mmol) and 2-methylfuran (**1a**) (225 μl, 2.5 mmol, 5 equiv) in dichloromethane (1.25 ml). The reaction mixture was stirred for 4 h at room temperature while controlling the reaction progress by TLC method. After the reaction was complete, the mixture was concentrated at reduced pressure. The product was isolated by column chromatography (eluent petroleum ether – CH_2Cl_2, 10:1). Yield 107 mg (75%), light-yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.25–2.30 (11H, m, $3CH_3$ and CH_2); 2.58 (2H, t, ^3J = 7.6, CH_2); 3.99 (1H, t, ^3J = 7.6, CH); 5.84–5.98 (6H, m, H furan). ^{13}C NMR spectrum, δ, ppm: 13.6; 13.7 (2C); 26.1; 31.4; 38.5; 105.8; 105.9; 106.1 (2C); 106.6 (2C); 150.4; 151.0 (2C); 153.6 (2C); 153.8. Found, *m*/*z*: 285.1489 $[M+H]^+$. $C_{18}H_{21}O_3$. Calculated, *m*/*z*: 285.1485.

Preparation of compounds 6a,b. $CuBr_2$ (1.7 mg, 1.5 mol %) was added to a solution of methyl vinyl ketone (**2p**) (41 μl, 0.5 mmol) and indole **5** (0.5 mmol) in dichloromethane (1.25 ml). The mixture was stirred for 4 h at room temperature while controlling the reaction prograss by TLC. Upon comletion, the mixture was concentrated at reduced pressure. The product was isolated by column chromatography (eluent petroleum ether – CH_2Cl_2, 10:1).

4-(1*H*-Indol-3-yl)butan-2-one (6a).[22] Yield 77 mg (82%), white crystalline powder, mp 91–92°C (petroleum ether – CH_2Cl_2) (mp 92–93°C[20]). ^{1}H NMR spectrum, δ, ppm

(*J*, Hz): 2.14 (3H, s, CH_3); 2.85 (2H, t, ^3J = 7.4, CH_2); 3.07 (2H, t, ^3J = 7.4, CH_2); 6.98 (1H, s, H indole); 7.10–7.15 (1H, m, H indole); 7.17–7.22 (1H, m, H indole); 7.32–7.36 (1H, m, H indole); 7.59–7.61 (1H, m, H indole); 7.96 (1H, br. s, NH). ^{13}C NMR spectrum, δ, ppm: 19.6; 30.1; 44.3; 111.3; 115.5; 118.8; 119.5; 121.6; 122.2; 127.4; 136.6; 206.7.

4-(2-Methyl-1*H*-indol-3-yl)butan-2-one (6b).[22] Yield 71 mg (71%), yellow oil. ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 2.06 (3H, s, CH_3); 2.33 (3H, s, CH_3); 2.69 (2H, t, ^3J = 7.2, CH_2); 2.84 (2H, t, ^3J = 7.2, CH_2); 6.90–7.00 (2H, m, H indole); 7.23–7.25 (1H, m, H indole); 7.40–7.42 (1H, m, H indole); 10.65 (1H, br. s, NH). ^{13}C NMR spectrum, δ, ppm: 11.2; 18.1; 29.7; 43.8; 109.1; 110.3; 117.3; 118.0; 119.9; 127.9; 131.4; 135.2; 208.3.

A Supporting information file containing ^{1}H and ^{13}C NMR spectra of all synthesized compounds is available at the journal website at http://link.springer.com/journal/10593.

This work was supported by the Russian Foundation for Basic Research (grant 16-33-00101 mol_a) and the Ministry of Education and Science of the Russian Federation (contract No. 02.a03.0008).

References

1. (a) Kate, A. S.; Pearson, J. K.; Ramanathan, B.; Richard, K.; Kerr, R. G. *J. Nat. Prod*. **2009**, *72*, 1331. (b) Yodsaoue, O.; Karalai, C.; Ponglimanont, C.; Tewtrakul, S.; Chantrapromma, S. *Tetrahedron* **2011**, *67*, 6838. (c) Liu, Q.; Ahn, J. H.; Kim, S. B.; Lee, C.; Hwang, Y. B.; Lee, M. K. *Phytochemistry* **2013**, *87*, 112. (d) Cheng, Y.-B.; Chien, Y.-T.; Lee, J.-C.; Tseng, C.-K.; Wang, H.-C.; Lo, I-W.; Wu, Y.-H.; Wang, S.-Y.; Wu, Y.-C.; Chang, F.-R. *J. Nat. Prod*. **2014**, *77*, 2367. (e) Bai, W.; Jin, X.; Jia, X.; Tang, W.; Wang, X.; Zhao, Y. *Phytochem. Lett*. **2014**, *10*, 118. (f) Bel, M. D.; Abela, A. R.; Ng, J. D.; Guerrero, C. A. *J. Am. Chem. Soc*. **2017**, *139*, 6819.
2. (a) Hansen, S. W.; Erichsen, M. N.; Fu, B.; Bjorn-Yoshimoto, W. E.; Abrahamsen, B.; Hansen, J. C.; Jensen, A. A.; Bunch, L. *J. Med. Chem*. **2016**, *59*, 8757. (b) Varano, F.; Catarzi, D.; Vincenzi, F.; Betti, M.; Falsini, M.; Ravani, A.; Borea, P. A.; Clotta, V.; Varani, K. *J. Med. Chem*. **2016**, *59*, 10564. (c) Carbajales, C.; Azuaje, J.; Oliveira, A.; Loza, M. I.; Brea, J.; Cadavid, M. I.; Masaguer, C. F.; Garcia-Mera, X.; Gutierrez-de-Teran, G.; Sotelo, E. *J. Med. Chem*. **2017**, *60*, 3372. (d) Jimenez-Somarribas, A.; Mao, S.; Yoon, J.-J.; Weisshaar, M.; Cox, R. M.; Marengo, J. R.; Mitchell, D. G.; Morehouse, Z. P.; Yan, D.; Solis, I.; Liotta, D. C.; Natchus, M. G.; Plemper, R. K. *J. Med. Chem*. **2017**, *60*, 2305.
3. (a) *Biopolymers – New Materials for Sustainable Films and Coatings*; Plackett, D., Ed.; John Wiley & Sons, Ltd., 2011, p. 179. (b) Yiu, A. Y.; Beaujuge P. M.; Lee, O. P.; Woo, C. H.; Toney, M. F.; Frechet, J. M. *J. Am. Chem.Soc*. **2012**, *134*, 2180. (c) Gandini, A.; Lacerda, T. M.; Carvalho, A. J.; Trovatti, E. *Chem. Rev*. **2016**, *116*, 1637.
4. (a) *Introduction to Chemicals from Biomass*; Clark, J. H.; Deswarte, F., Eds.; John Wiley & Sons, Ltd., 2015. (b) Husson, J.; Dehaudt, J.; Guyard, L. *J. Environ. Chem. Eng*. **2015**, *3*, 2292. (c) Liu, B.; Zhang, Z. *ChemSusChem* **2016**, *9*, 2015. (d) Chernyshev, V. M.; Kravchenko, O. A.; Ananikov, V. P. *Russ. Chem. Rev*. **2017**, *86*, 357. [*Usp. Khim.*, **2017**, *86*, 357.]
5. (a) Trushkov, I. V.; Uchuskin, M. G.; Butin, A. V. *Eur. J. Org. Chem*. **2015**, *14*, 2999. (b) Merkushev, A. A. *Chem. Heterocycl. Compd*. **2016**, *52*, 359. [*Khim. Geterotsikl. Soedin*. **2016**, *52*, 359.] (c) Abaev, V. T.; Trushkov, I. V.; Uchuskin, M. G. *Chem. Heterocycl. Compd*. **2016**, *52*, 973. [*Khim. Geterotsikl. Soedin*. **2016**, *52*, 973.]
6. (a) Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*; Oxford University Press, 1998, p. 30. (b) Beach, E. S.; Cui, Z.; Anastas, P. T. *Energy Environ. Sci*. **2009**, *2*, 1038. (c) Anastas, P.; Eghbali, N. *Chem. Soc. Rev*. **2010**, *39*, 301.
7. (a) Schnurch, M.; Dastbaravardeh, N.; Ghobrial, M.; Mrozek, B.; Mihovilovic, M. D. *Curr. Org. Chem*. **2011**, *15*, 2694. (b) Sharma, A.; Vacchani, D.; Van der Eycken, E. *Chem.–Eur. J*. **2013**, *19*, 1158. (c) Wei, Y.; Hu, P.; Zhang, M.; Su, W. *Chem. Rev*. **2017**, *117*, 8864.
8. (a) Uchuskin, M. G.; Makarov, A. S.; Butin, A. V. *Chem. Heterocycl. Compd*. **2014**, *50*, 791. [*Khim. Geterotsikl. Soedin*. **2014**, 860.] (b) Santos, F. M.; Batista, J. H. C.; Vessecchi, R.; Clososki, G. C. *Synlett* **2015**, 2795.
9. (a) Wetzel, A.; Pratsch, G.; Kolb, R.; Heinrich, M. R. *Chem.–Eur. J*. **2010**, *16*, 2547. (b) Pratsch, G.; Anger, C. A.; Ritter, K.; Heinrich, M. R. *Chem.–Eur. J*. **2011**, *17*, 4104. (c) Chalikidi, P. N.; Nevolina, T. A.; Uchuskin, M. G.; Abaev, V. T.; Butin, A. V. *Chem. Heterocycl. Compd*. **2015**, *51*, 621. [*Khim. Geterotsikl. Soedin*. **2015**, *51*, 621.]
10. (a) Zhao, J.; Huang, L.; Cheng, K.; Zhang, Y. *Tetrahedron Lett*. **2009**, *50*, 2758. (b) Zhang, Y.; Li, Z.; Liu, Z. Q. *Org. Lett*. **2012**, *14*, 226. (c) Pei, K.; Jie, X.; Zhao, H.; Su, W. *Eur. J. Org. Chem*. **2014**, *20*, 4230. (d) Bheeter, C. B.; Chen, L.; Soulé, J.-F.; Doucet, H. *Catal. Sci. Technol*. **2016**, *6*, 2005.
11. (a) Jiang, Q.; Guo, T.; Wu, K.; Yu, Z. *Chem. Commun*. **2016**, *52*, 2913. (b) Correia, J. T. M.; List, B.; Coelho, F. *Angew. Chem., Int. Ed*. **2017**, *56*, 7967. (c) Hayashi, M.; Matsubara, R. *Tetrahedron Lett*. **2017**, *58*, 1793.
12. (a) Alder, K.; Schmidt, C.-H. *Chem. Ber*. **1943**, *76*, 183. (b) Poirier, J.-M.; Dujardin, G. *Heterocycles* **1987**, *25*, 399. (c) Gerlach, H.; Huber, E. *Helv. Chim. Acta* **1967**, *50*, 2087. (d) Akhmedov, Sh. T.; Sadykhov, N. S.; Akhmedova, R. Sh.; Zefirov, N. S. *Chem. Heterocycl. Compd*. **1981**, *17*, 1158. [*Khim. Geterotsikl. Soedin*. **1981**, 1593.] (e) Chau, C. M.; Liu, K. M. *Org. Biomol. Chem*. **2008**, *6*, 3127. (f) Alder, R. W.; Hyland, N. P.; Jeffery, J. C.; Riis-Johannessen, T.; Riley, D. J. *Org. Biomol. Chem*. **2009**, *7*, 2704.
13. (a) Straub, B. F. *Organotransition Metal Chemistry: From Bonding to Catalysis*; Hartwig, J. F., Ed.; University Science Books, 2011. (b) *Lewis Acids in Organic Synthesis*; Yamamoto, H., Ed.; Wiley–VCH, 2000.
14. (a) Bulbule, V. J.; Deshpande, V. H.; Bedekar, A. V. *J. Chem. Res., Synop*. **2000**, 220. (b) Hashmi, A. S. K.; Schwarz, L.; Choi, J.-H.; Frost, T. M. *Angew. Chem., Int. Ed*. **2000**, *39*, 2285. (c) Dyker, G.; Muth, E.; Hashmi, A. S. K.; Ding, L. *Adv. Synth. Catal*. **2003**, *345*, 1247. (d) Hashmi, A. S. K.; Grundl, L. *Tetrahedron* **2005**, *61*, 6231. (e) Li, Z.; Shi, Z.; He, C. *J. Organomet. Chem*. **2005**, *690*, 5049. (f) Lin, Y. D.; Kao, J. Q.; Chen, C. T. *Org. Lett*. **2007**, *9*, 5195. (g) Aguilar, D.; Contel, M.; Navarro, R.; Soler, T.; Urriolabeitia, E. P. *J. Organomet. Chem*. **2009**, *694*, 486. (h) Leuger, J.; Blond, G.; Billard, T.; Haufe, G.; Langlois, B. R. *J. Fluorine Chem*. **2011**, *132*, 799. (i) Zhang, X.; Yu, X.; Feng, X.; Bao, M. *Synlett* **2012**, 1605. (j) Das, D.; Pratihar, S.; Roy, S. *J. Org. Chem*. **2013**, *78*, 2430. (k) Bagi, A. H.; Khaledi, Y.; Ghari, H.; Arndt, S.; Hashmi, A. S.; Yates, B. F.; Ariafard, A. *J. Am. Chem. Soc*. **2016**, *138*, 14599. (l) Metz, T. L.; Evans, J.; Stanley, L. M. *Org. Lett*. **2017**, *19*, 3442.
15. Makarov, A. S.; Fadeev, A. A.; Uchuskin, M. G.; Sorotskaya, L. N.; Trushkov, I. V.; Butin, A. V. RU patent 2602501; *Byul. Izobret*. **2016**, (32).

16. (a) Evano, G.; Blanchard, N.; Toumi, M. *Chem. Rev*. **2008**, *108*, 3054. (b) Poulsen, T. B.; Jorgensen, K. A. *Chem. Rev*. **2008**, *108*, 2903. (c) Guo, X. X.; Gu, D. W.; Wu, Z.; Zhang, W. *Chem. Rev.* **2015**, *115*, 1622. (d) Zhu, X.; Chiba, S. *Chem. Soc. Rev.* **2016**, *45*, 4504.
17. (a) Hashmi, A. S. K.; Schwarz, L.; Rubenbauer, P.; Blanco, M. C. *Adv. Synth. Catal.* **2006**, *348*, 705. (b) Shiri, M.; Zolfigol, M. A.; Ayazi-Nasrabadi, R. *Tetrahedron Lett.* **2010**, *51*, 264.
18. (a) Webb, I. D.; Borcherdt, G. T. *J. Am. Chem. Soc.* **1951**, *73*, 752. (b) Li, J. J. *Name Reactions. A Collection of Detailed Mechanisms and Synthetic Applications*; Springer: Cham, Heidelberg, New York, Dordrecht, London, 2014, p. 397.
19. (a) Fitzpatrick, J. E.; Milner, D. J.; White, P. *Synth. Commun*. **1982**, *12*, 489. (b) Haner, J.; Jack, K.; Nagireddy, J.; Raheem, M. A.; Durham, R.; Tam, W. *Synthesis* **2011**, 731. (c) Sivamani, J.; Ashokkumar, V.; Sadhasivam, V.; Duraimurugan, K.; Siva, A. *RSC Adv*. **2014**, *4*, 60293. (d) Orlov, V. D.; Vorob'eva, N. P.; Tischenko A. A.; Pikalev, O. M.; Popov, V. I., Yagupolskii, L. M. *Chem. Heterocycl. Compd*. **1991**, *27*, 942. [*Khim. Geterotsikl. Soedin.* **1991**, 1179.] (e) Therkelsen, F. D.; Hansen, A.-L. L.; Pedersen, E. B.; Nielsen, C. *Org. Biomol. Chem*. **2003**, *1*, 2908.
20. Yu, X.-Q.; Shirai, T.; Yamamoto, Y.; Miyaura, N. *Chem.–Asian J.* **2011**, 932.
21. Li, W.; Werner, T. *Org. Lett.* **2017**, *19*, 2568.
22. Yadav, J. S.; Abraham, S.; Reddy, B. V. S.; Sabitha, G. *Synthesis* **2001**, 2165.