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An improved iron-mediated synthesis of *N*-2-aryl substituted 1,2,3-triazoles†

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Treatment of various chalcones and sodium azide in the presence of catalytic amounts of commercially available iron oxide nanoparticles, followed by the addition of aryl halides afforded *N*-2-arylated 1,2,3-triazoles in very good yields. This tandem three-component reaction involves an oxidative 1,3-dipolar cycloaddition of the chalcone and azide and subsequent regioselective *N*-2-arylation. The nano-catalyst is easily recoverable and can be reused without any significant loss in catalytic activity.

Introduction

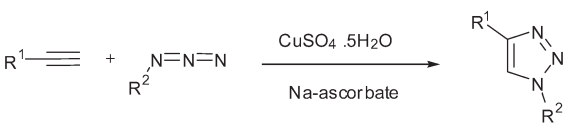
Ever since the advent of click chemistry (Scheme 1),[1] the synthesis of 1,2,3-triazoles and their applications in various areas[2,3] such as medicinal chemistry, chemical biology and material science have become popular and fruitful realms of research. The 1,2,3-triazole moiety is an important heterocyclic pharmacophore that function as integral structural fragment of a number of biologically active compounds such as kinase inhibitors,[4] anti-HIV agents,[5] antimicrobials[6] and anticancer agents.[7] Although click chemistry and functionalization of triazoles and its derivatives deliver a variety of *N*-1-substituted 1,2,3-triazoles[8] in a very efficient manner, methods for the synthesis of *N*-2-substituted-1,2,3-triazoles are rare.[9]

Yamamoto and coworkers reported a Pd(0)–Cu(I) catalyzed three component coupling reaction of allyl carbonate, alkynes and $TMSN_3$ to afford 2,4-disubstituted 1,2,3-triazoles.[9a] Chen and coworkers reported a metal and base free regioselective three-component reaction involving ynones, sodium azide and alkyl halides to generate 2,4,5-trisubstituted 1,2,3-triazoles (Scheme 2, eqn (1)).[10] Recently, the same group also reported a CuO-promoted one-pot synthesis of *N*-2-aryl substituted 1,2,3-triazoles *via* an azide–chalcone oxidative cycloaddition and post-triazole *N*-arylation (Scheme 2, eqn (2)).[11] It may be noted that the protocol requires the use of stoichiometric quantities of CuO. In view of the above-mentioned importance of 1,2,3-triazoles, a catalytic method for accessing *N*-2-arylated-1,2,3-triazoles assumes importance.

Catalysis of organic transformations by nanoparticles is an emerging area that has received significant attention in recent years.[12] Low catalyst loading resulting from the enhanced surface area per unit mass, ease of separation of products from the catalyst, recyclability and affordability are certain advantages that nanoparticle catalysts offer over bulk materials.[13] Therefore, we were intrigued by the possibility of developing a synthesis of *N*-2-aryl-1,2,3-triazoles by employing a readily available, affordable, non-toxic and environmentally friendly metal oxide nanoparticle as catalyst. Iron oxides and a few iron salts were selected as potential catalysts for the process as they satisfy the above-described criteria.[14,15]

Results and discussion

We initiated our studies by using (*E*)-1,3-bis(4-fluorophenyl) prop-2-en-1-one (**1a**) as a representative substrate with different Fe sources and solvents at variant temperatures (Table 1). Pleasingly, the treatment of a 1 : 1 mixture of **1a**, sodium azide with 10.0 mol%, commercially available Fe_3O_4 nanoparticles in DMSO (2 mL) at 70 °C and subsequent addition of 2-NO_2-C_6H_4F (**2a**) afforded *N*-2 arylated product **3a** in 65% yield (Table 1, entry 1; the reaction was conducted in an open flask). Inspired by this observation, different sources of iron, such as Fe_2O_3 nanoparticles, $FeSO_4{\cdot}7H_2O$, $FeCl_3$, $FeBr_2$, $Fe(acac)_2$ and bulk-Fe_2O_3 were screened for their catalytic activity (Table 1, entries 2–6 and 16). Among them,



Scheme 1 Click chemistry approach to 1,2,3-triazoles.

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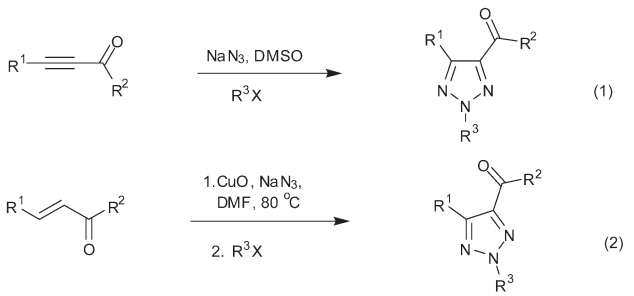
† Electronic supplementary information (ESI) available: Experimental procedures, powder XRD spectra, ^1H NMR and ^{13}C NMR spectroscopic data of all the compounds. CCDC reference number of the compound **3m**, 900346. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c3ra22485f

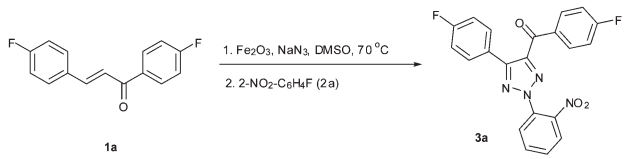


Scheme 2 Chen's synthesis of *N*-2-aryl-1,2,3-triazoles.

commercially available nano-Fe_2O_3 (<50 nm) was found perform best affording the desired product in 89% yield (Table 1, entry 2).

Interestingly, on decreasing the loading of Fe_2O_3 nanoparticles to 5 mol% enhanced the yield of the product to 92% (Table 1, entry 7). However, upon further decreasing the loading of Fe_2O_3 nanoparticles to 2 mol% reduced the yield to 69% (Table 1, entry 8). 5 mol% of the catalyst was found to be optimal for this conversion. Additionally, the role of the solvent was also investigated; it was observed that DMSO is the most suitable solvent for this reaction whereas solvents such as DMF and CH_3CN afforded the product in lower yields (Table 1, entries 9, 10). Solvents like EtOH, 1,4-dioxane and H_2O failed to produce the desired product (Table 1, entries 11–13). Meanwhile, the effect of temperature was also examined and it was observed that desired product was not formed at room temperature whereas enhancing the temperature to 100 °C did not improve the yield of the product (Table 1, entries 14–15). Finally, a blank reaction was conducted excluding catalyst to know the role of the catalyst (Table 1, entry 16); no product was formed in this experiment and the starting materials remained as such. Therefore, catalyst plays an important role in this oxidative dehydrogenative coupling reaction.

Table 1 Optimization of various Fe sources[a]



Entry	Fe	Solvent	T (°C)	Mol (%)	Yield[b] (%)
1	Nano-Fe_3O_4	DMSO	70	10.0	65
2	Nano-Fe_2O_3	DMSO	70	10.0	89
3	$FeSO_4 \cdot 7H_2O$	DMSO	70	10.0	45
4	$FeCl_3$	DMSO	70	10.0	30
5	$FeBr_2$	DMSO	70	10.0	None
6	$Fe(acac)_2$	DMSO	70	10.0	40
7	Nano-Fe_2O_3	DMSO	70	5.0	92
8	Nano-Fe_2O_3	DMSO	70	2.0	69
9	Nano-Fe_2O_3	DMF	70	10.0	68
10	Nano-Fe_2O_3	CH_3CN	70	5.0	51
11	Nano-Fe_2O_3	1,4-Dioxane	70	5.0	None
12	Nano-Fe_2O_3	EtOH	70	5.0	Trace
13	Nano-Fe_2O_3	H_2O	70	5.0	None
14	Nano-Fe_2O_3	DMSO	Rt	5.0	None
15	Nano-Fe_2O_3	DMSO	100	5.0	75
16	Bulk-Fe_2O_3	DMSO	70	5.0	49
17	None	DMSO	70	None	None

[a] Reaction conditions: all of the reactions were carried out with substrate **1a** (0.3 mmol), NaN_3 (0.3 mmol), and 5.0 mol% of Fe_2O_3 nanoparticles in the solvent DMSO (2 mL) at 70 °C under air for 18 h followed by the addition of 2-NO_2-C_6H_4F (**2a**) (0.3 mmol) to the reaction mixture and continued for 4 h. [b] Isolated yields.

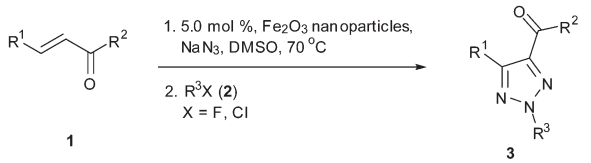
Under the optimized conditions, the scope of the methodology was investigated with various chalcones and the results are described in Table 2. Chalcones with electron-withdrawing groups on R^1 and/or R^2 gave higher yields (**3a–e**, **3r** and **3s**; Table 2, entries 1–5 and 18, 19) consistent with the observation made by Chen.[11] On the other hand, chalcones with electron-donating groups produced comparatively lower yields of the products (Table 2, entries 6–17). In addition, replacing the carbonyl attached aromatic ring of the chalcone R^2 of **1a** with the five membered heterocycles such as thiophene and pyrrole (Table 2, entries 20–21) did not afford the desired products and decomposition of starting materials were observed. Chalcones derived from α,β-unsaturated carbonyl compounds such as *trans*-cinnamaldehyde, ethyl acrylate and methyl cinnamate, did not react under these optimized conditions and the starting materials were recovered from the reaction mass. The α,β-unsaturated aldehydes and esters also failed to participate in this reaction.

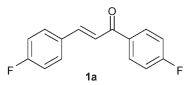
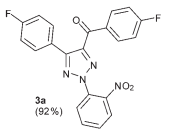
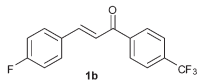
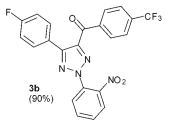
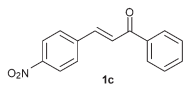
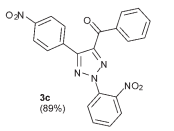
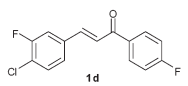
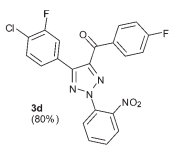
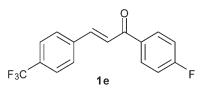
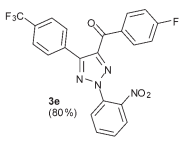
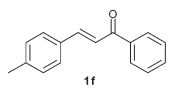
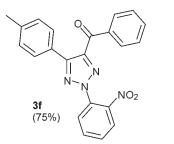
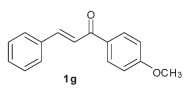
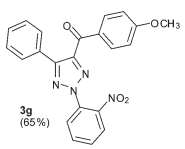
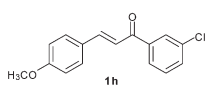
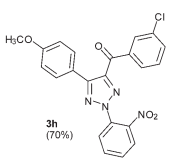
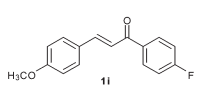
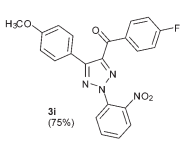
The aryl halide component (**2a–f**) of the reaction can also be varied to include electron-deficient aryl halides, such as, 2-NO_2-C_6H_4F (**2a**), 3,4-difluoro-$C_6H_3NO_2$ (**2b**) and 2,4-dinitro-C_6H_3Cl (**2c**) to furnish the corresponding 2,4,5-trisubstituted 1,2,3-triazoles. However, this reaction using 2-NO_2-C_6H_4Cl (**2d**) and 2-Cl, 4-NO_2-C_5H_3N (**2e**) and electron rich aryl chloride 2-CH_3-C_6H_4Cl (**2f**) did not yield the desired products (Table 2, entries 22–24). Finally, confirmation of the structure and the site of *N*-arylation of the product were obtained by the single crystal X-ray analysis of **3m** (Fig. 1).

It is evident that the triazoles are formed *via* an oxidative cycloaddition and in order to gain insight into the mechanism of this conversion, the reaction between **1a** and **2a** was conducted under a nitrogen atmosphere using 5.0 mol% of Fe_2O_3 nanoparticles. A lower yield of the product **3a** (40%) was obtained even after the best efforts were made to exclude oxygen. Additionally, no product was formed in the absence of the catalyst under aerobic conditions (Table 1, entry 17). Therefore, it is clear that atmospheric oxygen acts as the sacrificial oxidant only in the presence of the catalyst. It is presumable that the Fe(III) species in the catalyst is responsible for the oxidation and atmospheric oxygen regenerates the catalytically active species by re-oxidation of the low-valent iron intermediates. Further investigations are required to unravel the details of the catalytic cycle and mechanism of this intriguing transformation.

Another advantage of the present method is the reusability of the nano-Fe_2O_3. The catalyst gets adhered to the magnetic stirring bar once the latter is stationary and thus can be easily

Table 2 Iron-promoted tandem reactions of chalcones with arylhalides for the synthesis of *N*-2-aryl-1,2,3-triazoles[a]



Entry	1	2	3 (Yield[b])
1			
2		**2a**	
3		**2a**	
4		**2a**	
5		**2a**	
6		**2a**	
7		**2a**	
8		**2a**	
9		**2a**	

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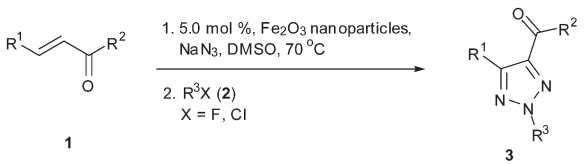

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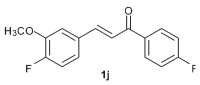
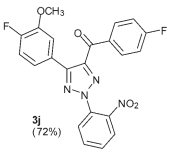
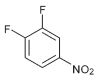
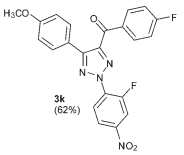
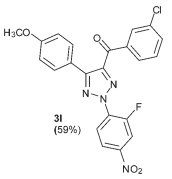
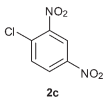
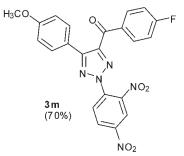
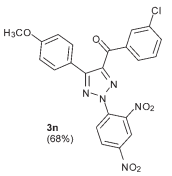
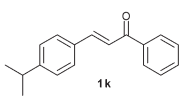
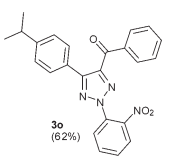
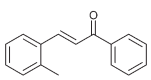
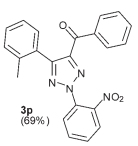
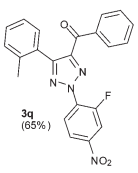
10		**2a**	
11	**1i**		
12	**1h**	**2b**	
13	**1i**		
14	**1h**	**2c**	
15		**2a**	
16		**2a**	
17	**1l**	**2b**	

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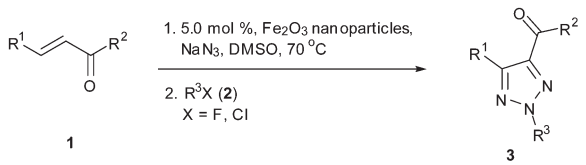
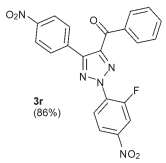
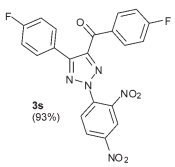
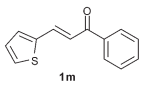
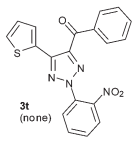
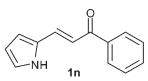
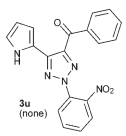
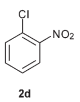
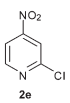
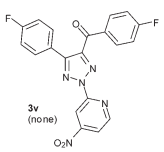
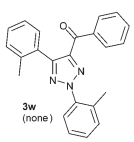


Entry	1	2	3 (Yield[b])
18	**1c**	**2b**	
19	**1a**	**2c**	
20		**2a**	
21		**2a**	
22	**1l**		**3p** (None)
23	**1a**		
24	**1l**		

[a] All of the reactions were carried out with substrate **1a** (0.3 mmol), NaN_3 (0.3 mmol), and 5.0 mol% of Fe_2O_3 nanoparticles in the solvent DMSO (2 mL) at 70 °C under air for 18 h followed by the addition of 2-NO_2-C_6H_4F (**2a**) (0.3 mmol) to the reaction mixture, and continued for 4 h. [b] Isolated yields in %.

recovered. The recovered catalyst was reused after sequential washing with ethyl acetate and acetone followed by drying in a hot air oven at 80 °C. Remarkably, no significant loss in catalytic activity was observed over three cycles of use for the catalyst (Table 3). It was evident from the Powder-XRD spectral studies and SEM-analysis that there was no change in the nature of the catalyst even after the third cycle.[16]

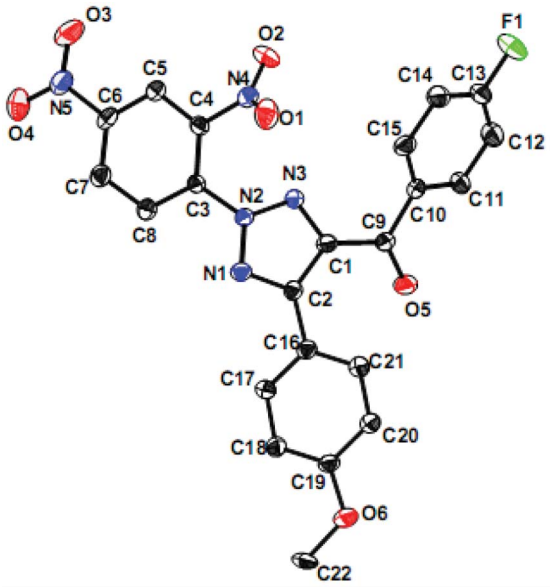


Fig. 1 Single crystal X-ray structure of **3m**.

Conclusions

In summary, we have developed a new Fe_2O_3 nanoparticle catalyzed three-component reaction for the construction of 2,4,5-trisubstituted-1,2,3-triazole from chalcones, sodium azide and aryl halides. The reaction has good substrate scope and furnishes the products in very good yields. Importantly, the catalyst is easily recoverable and may be reused without any significant loss in catalytic activity. Control experiments suggest that atmospheric oxygen acts as the sacrificial oxidant in the reaction. The biological evaluation of the synthesized *N*-2-aryl-substituted-1,2,3-triazoles (**3a–s**) is ongoing in our laboratory and will be communicated in due course.

Experimental section

General methods

Reactions were monitored by TLC, performed on silica gel glass plates containing 60 F-254 and visualization on TLC was achieved by UV light or iodine indicator. Column chromato-

Table 3 Recycling of Fe_2O_3 nanoparticles

Recycles	Catalyst recovery (wt%)	Yield of **3a** (%)
1	90	92
2	88	89
3	85	86

graphy was performed with Merck (Navi Mumbai, India) 60–120 mesh silica gel. Spectral patterns were designated as s, singlet; d, doublet; dd, double doublet; t, triplet; td, triplet doublet; m, multiplet. ^{1}H NMR and ^{13}C NMR were spectra were recorded on Avance 300 MHz and 75 MHz (Bruker, Fallanden, Switzerland) instruments. Chemical shifts (δ) were reported in ppm, downfield from internal TMS standard. ESI spectra were recorded on Micro mass, Quattro LC using ESI software with capillary voltage of 3.98 kV and ESI mode positive ion trap detector. High-resolution mass spectra (HRMS) were recorded on QSTAR XL Hybrid MS/MS mass spectrometer. IR spectra were recorded on a FT-IR spectrometer and only major peaks are reported in cm^{-1}. Melting points were determined on a microscopic apparatus and were uncorrected. Starting materials and reagents were purchased from Lancaster (Alfa Aesar, Johnson Matthey Co, Ward Hill, MA, USA), Sigma-Aldrich (St Louis, MO, USA) and Spectrochem Pvt Ltd (Mumbai, India).

General procedure for synthesis of chalcones 1a–n

The following procedure is representative synthesis of all chalcones. The substituted acetophenone (0.5 mmol) and NaOH (0.1 mmol) were dissolved in 20 mL ethanol, and taken in a round bottom of flask equipped with stirrer. The reaction was stirred at 0–5 °C; then the aldehyde was dissolved in 10 mL ethanol and added dropwise for 30 min, then the reaction was allowed to continue for 5 h at room temperature. The residual mass was quenched in the ice–water mixture and neutralized with 10% HCl solution. Then chromatography separation was followed by recrystallization from 95% ethanol in increasing order of polarity.

The general procedure for the synthesis of compounds 3a–s

All reactions were performed on a 0.30 mmol scale relative to chalcones. The α,β-unsaturated carbonyl compound (**1**) (0.30 mmol), sodium azide (0.20 mmol) 5 mol% Fe_2O_3 and 2 mL DMSO were taken in a round bottom flask equipped with stirrer. The reaction mixture was stirred at 70 °C for 18 h, then arylnitrohalides (**2**) (0.30 mmol) were added to the mixture and the reaction continued at 70 °C for 4 h. To the reaction mixture, water (5 mL) was added and extracted with ester (3 × 10 mL). The combined organic phases were washed with brine (2 × 5 mL), dried over anhydrous Na_2SO_4 and concentrated *in vacuo*. The reaction mass was subjected to flash column chromatography with hexanes/EtOAc (5 : 1) as eluent to obtain the desired product **3**. All of the substituted triazoles were prepared in the similar manner and their characterization data are as follows:

Spectral data of the compounds

(4-Fluorophenyl)(5-(4-fluorophenyl)-2-(2-nitrophenyl)-2*H*-1,2,3-triazol-4-yl)methanone (3a)

Eluent: hexane–ethylacetate (5 : 1). Orange yellow solid (92%, 111 mg), mp: 130–131 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.17–8.12 (m, 2H), 8.02 (dd, J = 6.7 Hz, 1.5 Hz, 1H), 7.95–7.90 (m, 3H), 7.78 (td, J = 6.0 Hz, 1.5 Hz, 1H), 7.65 (td, J = 6.7 Hz, 1.5 Hz, 1H), 7.22–7.12 (m, 4H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.4, 167.8, 164.4, 150.5, 143.4, 133.3, 131.9, 129.8, 125.5, 124.9, 115.7, 115.6, 115.4, 115.3. IR (KBr): ν_{max} 3077, 1651, 1539 cm^{-1}. ESI HRMS: calcd. for $C_{21}H_{12}O_3N_4F_2Na$ [M + Na]$^+$: 429.07697, found: 429.07798.

(5-(4-Fluorophenyl)-2-(2-nitrophenyl)-2*H*-1,2,3-triazol-4-yl)(4-(trifluoromethyl)phenyl)-methanone (3b)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (90%, 122 mg), mp: 95–96 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.20 (d, J = 8.3 Hz, 2 H, Ar), 8.02 (dd, J = 6.7 Hz, 1.5 Hz, 1 H, Ar), 7.99–7.93 (m, 3 H, Ar), 7.81–7.76 (m, 3 H, Ar), 7.68–7.63 (td, J = 6.0 Hz, 1.5 Hz, 1 H, Ar), 7.17 (t, J = 6.0 Hz, 2 H, Ar) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.0, 165.4, 139.5, 133.1, 131.6, 131.2, 131.1, 130.0, 126.1, 125.6, 125.4, 125.0, 124.6, 118.6, 116.9, 115.7, 115.4 ppm. IR (KBr): ν_{max} 2995, 2358, 1666, 1546 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{13}O_3N_4F_4$ [M + H]$^+$: 457.09183, found: 457.09271.

(2-(2-Nitrophenyl)-5-(4-nitrophenyl)-2*H*-1,2,3-triazol-4-yl)(phenyl)methanone[11] (3c)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (109 mg, yield: 89%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.29 (d, J = 8.7 Hz, 2 H, Ar), 8.12 (t, J = 8.7 Hz, 4 H, Ar), 8.02 (d, J = 8.7 Hz, 1 H, Ar), 7.97 (d, J = 7.8 Hz, 1 H, Ar), 7.80 (t, J = 7.8 Hz, 1 H, Ar), 7.69 (d, J = 7.8 Hz, 1 H, Ar), 7.65 (d, J = 6.8 Hz, 1 H, Ar), 7.53 (t, J = 7.8 Hz, 2 H, Ar) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.9, 149.2, 148.3, 144.4, 143.8, 136.3, 135.0, 134.1, 133.2, 131.7, 130.5, 130.2, 129.8, 128.5, 125.8, 125.2, 123.6 ppm.

(5-(4-Chloro-3-fluorophenyl)-2-(2-nitrophenyl)-2*H*-1,2,3-triazol-4-yl)(4-fluorophenyl)methanone (3d)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (108 mg, yield: 80%), mp: 91–92 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.17–8.12 (m, 2H), 8.01 (d, J = 8.3 Hz, 1H), 7.96 (d, J = 8.3, 1H), 7.84–7.77 (m, 2H), 7.72–7.64 (m, 2H), 7.48 (t, J = 7.5 Hz, 1H), 7.20 (t, J = 9.0 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.1, 165.5, 164.7, 149.7, 144.0, 139.9, 133.4, 132.6, 130.7, 128.6, 127.5, 125.3, 117.3, 117.0, 116.8, 115.9, 115.6, 113.5, 113.1. IR (KBr): ν_{max} 3080, 1655, 1540 cm^{-1}. ESI HRMS: calcd. for $C_{21}H_{12}O_3N_4ClF_2$ [M + H]$^+$: 441.05644, found: 441.05605.

(4-Fluorophenyl)(2-(2-nitrophenyl)-5-(4-(trifluoromethyl)phenyl)-2*H*-1,2,3-triazol-4-yl)methanone (3e)

Eluent: hexane–ethylacetate (5 : 1). Yellow solid (80%, 108 mg), mp: 91–92 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.19–8.13 (m, 2H), 8.05 (d, J = 8.0 Hz, 3H), 7.96 (dd, J = 6.7, 1.5 Hz, 1H), 7.80 (td, J = 6.7, 1.5 Hz, 1H), 7.71 (d, J = 8.3 Hz, 2H), 7.67 (td, J = 6.7, 1.5 Hz, 1H), 7.23–7.14 (m, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.3, 168.0, 150.1, 143.7, 133.3, 133.2, 133.1, 132.5, 132.1, 131.6, 130.1, 129.3, 125.7, 125.3, 125.1, 118.9, 115.9, 115.6. IR (KBr): ν_{max} 3080, 1655, 1540 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{13}O_3N_4F_4$ [M + H]$^+$: 457.09183, found: 457.09275.

(2-(2-Nitrophenyl)-5-*p*-tolyl-2*H*-1,2,3-triazol-4-yl)(phenyl)methanone[11] (3f)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (85 mg, yield: 75%), mp: 152–153 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.04 (d, J = 8.0 Hz, 2H), 7.96 (d, J = 8.0 Hz, 1H), 7.84 (d, J = 8.0 Hz,

1H), 7.68 (t, J = 8.0 Hz, 1H), 7.56–7.51 (m, 2H), 7.41 (t, J = 8.0 Hz, 2H), 7.33 (d, J = 8.0 Hz, 1H), 7.28–7.16 (m, 4H), 2.21 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.6, 152.1, 145.5, 142.2, 137.6, 136.8, 133.9, 133.3, 132.3, 130.7, 130.1, 129.7, 129.0, 128.7, 126.0, 125.9, 125.3, 20.4.

(4-Methoxyphenyl)(2-(2-nitrophenyl)-5-phenyl-2*H*-1,2,3-triazol-4-yl)*m*-ethanone[11] (3g)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (77 mg, yield: 65%), mp: 139–140 °C. ^{1}H NMR (300 MHz, $CDCl_3$): 8.09–8.04 (m, 2H), 7.97 (d, J = 8.8 Hz, 1H), 7.86–7.79 (m, 3H), 7.70 (t, J = 8.0 Hz, 1H), 7.55 (t, J = 8.0 Hz, 1H), 7.19–7.09 (m, 3H), 6.91 (d, J = 8.8 Hz, 2H), 3.79 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.8, 164.5, 151.3, 143.4, 133.3, 133.2, 133.2, 133.0, 130.4, 129.6, 125.5, 125.0, 115.8, 115.5, 113.9, 55.3.

(3-Chlorophenyl)(5-(4-methoxyphenyl)-2-(2-nitrophenyl)-2*H*-1,2,3-tria-zol-4-yl)methanone (3h)

Eluent: hexane–ethylacetate (5 : 1). Yellow solid (90 mg, yield: 70%), mp: 101–102 °C. ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.08 (s, 1H), 8.03 (d, J = 7.9 Hz, 1.2 Hz 1H), 7.97–7.86 (m, 4H), 7.76 (t, J = 7.7 Hz, 1H), 7.64–7.57 (m, 2H), 7.45 (t, J = 8.0 Hz, 1H), 6.97 (d, J = 8.8 Hz, 2H), 3.86 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.9, 160.8, 151.4, 143.6, 143.1, 138.4, 134.6, 133.6, 132.9, 131.7, 130.41, 130.1, 129.6, 128.7, 125.5, 124.9, 120.8, 113.8, 55.2. IR (KBr): ν_{max} 2954, 1669, 1544 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{15}O_4N_4ClNa$: 457.06740, found: 457.06727.

(4-Fluorophenyl)(5-(4-methoxyphenyl)-2-(2-nitrophenyl)-2*H*-1,2,3-tria-zol-4-yl)methanone (3i)

Eluent: hexane–ethylacetate (5 : 1). Light yellow semi-solid (93 mg, yield: 75%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.16–8.11 (m, 2H), 8.03 (dd, J = 6.9 Hz, 1.2 Hz, 1H), 7.92 (dd, J = 6.9 Hz, 1.2 Hz, 1H), 7.88 (d, J = 8.6 Hz, 2H), 7.77 (td, J = 6.4 Hz, 1.2 Hz, 1H), 7.62 (td, J = 6.4 Hz, 1.2 Hz, 1H), 7.19 (t, J = 8.4 Hz, 2H), 6.98 (d, J = 8.6 Hz, 2H), 3.86 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.7, 167.8, 164.4, 160.7, 151.2, 134.6, 133.2, 133.1, 132.9, 131.7, 130.3, 129.5, 125.4, 124.9, 120.9, 115.7, 115.4, 113.8, 55.2. IR (KBr): ν_{max} 2954, 1669, 1544 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{16}O_4N_4F$ $[M + H]^+$: 419.11501, found: 419.11525.

(5-(4-Fluoro-3-methoxyphenyl)-2-(2-nitrophenyl)-2*H*-1,2,3-triazol-4-yl)(4-fluorophenyl)methanone (3j)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (120 mg, yield: 72%), mp: 101–102 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.19 (d, J = 8.3 Hz, 2H), 8.01 (dd, J = 6.7 Hz, 1.5 Hz, 1H), 7.92 (dd, J = 6.7 Hz, 1.5 Hz, 1H), 7.81–7.74 (m, 5H), 7.64 (td, J = 6.7 Hz, 1.5 Hz, 1H), 7.03 (t, J = 8.3 Hz, 1H), 3.92 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.0, 153.5, 150.6, 150.2, 149.1, 143.6, 143.0, 139.6, 133.0, 131.5, 130.7, 130.0, 125.5, 125.4, 125.3, 125.0, 16.9, 112.8, 56.1. IR (KBr): ν_{max} 3080, 1669, 1544 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{14}O_4N_4F_2Na$ $[M + Na]^+$: 459.08753, found: 459.08841.

(2-(2-Fluoro-4-nitrophenyl)-5-(4-methoxyphenyl)-2*H*-1,2,3-triazol-4-yl)(4-fluorophenyl)methanone (3k)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (79 mg, yield: 62%), mp: 121–122 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.30–8.20 (m, 3H), 8.04 (dd, J = 8.3 Hz, 3.0 Hz, 1H), 7.86 (d, J = 9.0 Hz, 1H), 7.61 (d, J = 8.3 Hz, 1H), 7.24 (s, 1H), 7.22–7.14 (m, 2H), 7.00–6.92 (m, 2H), 3.86 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.5, 161.7, 160.9, 144.8, 133.3, 130.9, 130.3, 130.2, 127.4, 124.7, 120.6, 119.9, 119.2, 115.8, 115.4, 144.4, 113.9, 55.39. IR (KBr): ν_{max} 3089, 2364, 1659, 1601, 1534 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{14}O_4N_4F_2Na$ $[M + Na]^+$: 459.08753, found: 459.08847.

(3-Chlorophenyl)(2-(2-fluoro-4-nitrophenyl)-5-(4-methoxyphenyl)-2*H*-1,2,3-triazol-4-yl)methanone (3l)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (81 mg, yield: 59%), mp: 183–184 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.27–8.17 (m, 4 H, Ar), 8.06 (d, J = 7.5 Hz, 1H), 7.88 (d, J = 8.3 Hz, 2H), 7.62 (d, J = 7.5 Hz, 1H), 7.47 (d, J = 8.3 Hz, 1H), 7.00 (d, J = 9.0 Hz, 2H), 3.87 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 197.3, 161.0, 151.8, 150.1, 143.6, 138.5, 138.2, 134.7, 133.6, 130.5, 130.4, 129.7, 128.6, 124.8, 120.5, 114.3, 114.0, 55.3. IR (KBr): ν_{max} 3083, 1670, 1535 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{14}O_4N_4ClFNa$ $[M + Na]^+$: 475.05798, found: 475.05808.

(2-(2,4-Dinitrophenyl)-5-(4-methoxyphenyl)-2*H*-1,2,3-triazol-4-yl)(4-fluorophenyl)methanone (3m)

Eluent: hexane–ethylacetate (5 : 1). light yellow solid (95 mg, yield: 70%), mp: 169–170 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.69 (d, J = 2.2 Hz, 1H), 8.58 (dd, J = 6.5, 2.2 Hz, 1H), 8.37 (d, J = 9.0 Hz, 1H), 8.14–8.09 (m, 2H), 7.85 (d, J = 8.3 Hz, 2H), 7.21 (d, J = 9.0 Hz, 2H), 6.98 (d, J = 9.0 Hz, 2H), 3.86 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.3, 161.2, 152.2, 146.3, 144.6, 134.8, 133.3, 133.1, 130.4, 127.1, 125.1, 120.7, 120.1, 116.0, 115.7, 114.1, 55.3. IR (KBr): ν_{max} 3087, 2359, 1660, 1536 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{15}O_6N_5F$ $[M + H]^+$: 464.10009, found: 464.10051.

(3-Chlorophenyl)(2-(2,4-dinitrophenyl)-5-(4-methoxyphenyl)-2*H*-1,2,3-triazol-4-yl)methanone (3n)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (96 mg, yield: 68%), mp: 136–137 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.67 (d, J = 2.1 Hz, 1H), 8.57 (dd, J = 6.5, 2.1 Hz, 1H), 8.36 (d, J = 8.7 Hz, 1H), 8.06 (s, 1H), 7.94 (d, J = 7.6 Hz, 1H), 7.85 (d, J = 8.7 Hz, 2H), 7.62 (d, J = 6.5 Hz, 1H), 7.47 (t, J = 7.6 Hz, 1H), 6.98 (d, J = 8.7 Hz, 2H), 3.87 (s, 3 H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.4, 161.2, 152.2, 146.3, 144.2, 142.3, 137.8, 134.8, 134.7, 133.8, 130.3, 130.0, 129.8, 128.6, 127.1, 125.1, 120.6, 119.9, 114.0, 55.3. IR (KBr): ν_{max} 3083, 1670, 1535 cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{15}O_6N_5Cl$ $[M + H]^+$: 480.07054, found: 480.07095.

(5-(4-Isopropylphenyl)-2-(2-nitrophenyl)-2*H*-1,2,3-triazol-4-yl)(phenyl)methanone (3o)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (76 mg, yield: 62%), mp: 132–133 °C. ^{1}H NMR (300 MHz, $CDCl_3$): 8.08 (dd, J = 7.5, 1.5 Hz, 2H), 8.03 (dd, J = 8.3, 1.5 Hz, 1H), 7.92 (dd, J = 8.3, 1.5 Hz, 1H), 7.83 (d, J = 8.3 Hz, 2H), 7.77 (td, J = 8.3, 1.5 Hz, 1H), 7.65–7.59 (m, 2H), 7.52 (t, J = 7.5 Hz, 2H), 7.30 (d, J = 8.3 Hz, 2H), 3.00–2.90 (m, 1H), 1.27 (dd, J = 6.7 Hz, 6H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 187.5, 151.4, 150.6, 7, 133.7, 132.9, 131.9, 130.4, 130.3, 129.5, 128.8, 128.7, 128.4, 126.5, 126.0, 125.6, 124.9, 34.0, 23.8. IR (KBr): ν_{max} 3065, 1655, 1561 cm^{-1}. ESI HRMS: calcd. for $C_{24}H_{21}O_3N_4$ $[M + H]^+$: 413.1613, found 413.1625.

(2-(2-Nitrophenyl)-5-*o*-tolyl-2*H*-1,2,3-triazol-4-yl)(phenyl)methanone (3p)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (78 mg, yield: 69%), mp: 142–143 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.12 (d, J = 7.9 Hz, 2H), 8.04 (d, J = 7.9 Hz, 1H), 7.92 (d, J = 7.9 Hz, 1H), 7.76 (t, J = 7.9 Hz, 1H), 7.62 (d, J = 8.9 Hz, 1H), 7.59 (d, J = 7.9 Hz, 1H), 7.49 (t, J = 7.9 Hz, 2H), 7.40 (d, J = 7.9 Hz, 1H), 7.34 (t, J = 6.9 Hz, 1H), 7.30–7.23 (m, 2 H), 2.29 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 186.2, 151.7, 145.0, 143.8, 137.1, 136.4, 133.5, 132.9, 131.9, 130.3, 130.3, 129.7, 129.3, 128.6, 128.3, 128.3, 125.7, 125.5, 124.9, 20.1. ESI HRMS: calcd. for $C_{22}H_{17}O_3N_4$ $[M + H]^+$: 385.1295, found: 385.1310.

(2-(2-Fluoro-4-nitrophenyl)-5-*o*-tolyl-2*H*-1,2,3-triazol-4-yl)(phenyl)methanone (3q)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (77 mg, yield: 65%), mp: 150–151 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.28 (t, J = 9.0 Hz, 1H), 8.25–8.20 (m, 4H), 7.62 (t, J = 7.0 Hz, 1H), 7.50 (t, J = 8.0 Hz, 2H), 7.39 (d, J = 7.0 Hz, 1H), 7.36 (d, J = 8.0 Hz, 1H), 7.31 (t, J = 7.0 Hz, 1H), 7.27 (d, J = 7.0 Hz, 1H), 2.30 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.9, 155.1, 152.0, 147.4, 145.6, 137.0, 136.3, 133.7, 132.3, 130.4, 130.4, 130.1, 129.6, 128.4, 125.7, 124.8, 120.0, 114.3, 113.9, 20.2. IR (KBr): ν_{max} cm^{-1}. ESI HRMS: calcd. for $C_{22}H_{16}O_3N_4F$ $[M + H]^+$: 403.1201, found: 403.1212.

(2-(2-Fluoro-4-nitrophenyl)-5-(4-nitrophenyl)-2*H*-1,2,3-triazo-l-4-yl)(phenyl)methanone (3r)

Eluent: hexane–ethylacetate (5 : 1). Light yellow solid (110 mg, yield: 86%), mp: °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.32 (d, J = 8.9 Hz, 2H), 8.28–8.26 (m, 3H), 8.19 (d, J = 6.9 Hz, 2H), 8.13 (d, J = 7.9 Hz, 2H), 7.69 (t, J = 6.9 Hz, 1H), 7.55 (t, J = 6.9 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.9, 156.7, 155.2, 151.7, 143.9, 143.6, 134.3, 130.6, 129.8, 128.6, 125.0, 123.7, 10.0, 114.4, 114.0. IR (KBr): ν_{max} 3094, 2925, 1662, 1515 cm^{-1}. ESI HRMS: calcd. for $C_{21}H_{13}O_5N_5F$ $[M + H]^+$: 434.09006, found: 434.09121.

(2-(2,4-Dinitrophenyl)-5-(4-fluorophenyl)-2*H*-1,2,3-triazol-4-yl)(4-fluorophenyl)methanone (3s)

Eluent: hexane–ethylacetate (5 : 1). Light white solid (125 mg, yield: 93%), mp: 166–167 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.71 (d, J = 2.2 Hz, 1H), 8.60 (dd, J = 6.0, 2.2 Hz, 1H), 8.37 (d, J = 9.0 Hz, 1H), 8.15–8.10 (m, 2H), 7.93–7.89 (m, 2H), 7.25–7.14 (m, 4H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 185.0, 165.6, 164.7, 146.5, 144.7, 134.8, 133.3, 133.2, 131.1, 131.0, 127.3, 125.3, 120.8, 116.0, 115.9, 115.7, 115.6. IR (KBr): ν_{max} 3096, 1663, 1545 cm^{-1}. ESI HRMS: calcd. for $C_{21}H_{13}O_5N_5F$ $[M + H]^+$: 452.08066, found: 452.08071.

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Notes and references

1 For reviews, see: (*a*) H. C. Kolb, M. G. Finn and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2001, **40**, 2004; (*b*) V. V. Rostovtsev, L. G. Green, V. V. Fokin and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2002, **41**, 2596; (*c*) P. Wu and V. V. Fokin, *Aldrichimica Acta*, 2007, **40**, 7.

2 (*a*) J. E. Moses and A. D. Moorhouse, *Chem. Soc. Rev.*, 2007, **36**, 1249; (*b*) H. C. Kolb and K. B. Sharpless, *Drug Discovery Today*, 2003, **8**, 1128; (*c*) F. Amblard, J. H. Cho and R. F. Schinazi, *Chem. Rev.*, 2009, **109**, 4207; (*d*) R. Breinbauer and M. Kohn, *ChemBioChem*, 2003, **4**, 1147; (*e*) V. D. Bock, H. Hiemstra and J. H. Van Maarseveen, *Eur. J. Org. Chem.*, 2006, 51; (*f*) A. Wang, N. W. Nairn, R. S. Johnson, D. A. Tirrell and K. Grabstein, *ChemBioChem*, 2008, **9**, 324; (*g*) P. Wu, A. K. Feldman, A. K. Nugent, C. J. Hawker, A. Scheel, B. Voit, J. Pyun, J. M. J. Fréchet, K. B. Sharpless and V. V. Fokin, *Angew. Chem., Int. Ed.*, 2004, **43**, 3928; (*h*) L. Zhang, X. Chen, P. Xue, H. H. Y. Sun, I. D. Williams, K. B. Sharpless, V. V. Fokin and G. Jia, *J. Am. Chem. Soc.*, 2005, **127**, 15998.

3 (*a*) V. D. Bock, D. Speijer, H. Hiemstra and J. H. van Maarseveen, *Org. Biomol. Chem.*, 2007, **5**, 971; (*b*) K. A. Winans and C. R. Bertozzi, *Chem. Biol.*, 1998, **5**, R313; (*c*) K. J. Yarema, L. K. Mahal, R. E. Bruehl, E. C. Rodriguez and C. R. Bertozzi, *J. Biol. Chem.*, 1998, **273**, 31168; (*d*) E. Saxon and C. R. Bertozzi, *Science*, 2000, **287**, 2007; (*e*) V. Aucagne, J. Berna, J. D. Crowley, S. M. Goldup, K. D. Haenni, D. A. Leigh, P. J. Lusby, V. E. Ronaldson, A. M. Z. Slawin, A. Viterisi and D. B. Walker, *J. Am. Chem. Soc.*, 2007, **129**, 11950; (*f*) A. Maliakal, G. Lem, N. J. Turro, R. Ravichandran, J. C. Suhadolnik, A. D. DeBellis, M. G. Wood and J. Lau, *J. Phys. Chem. A*, 2002, **106**, 7680.

4 S. B. Ferreira, A. C. R. Sodero, M. F. C. Cardoso, E. S. Lima, C. R. Kaiser, F. P. Silva and V. F. Ferreira, *J. Med. Chem.*, 2010, **53**, 2364.

5 (*a*) J. H. Cho, D. L. Bernard, R. W. Sidwell, E. R. Kern and C. K. Chu, *J. Med. Chem.*, 2006, **49**, 1140; (*b*) M. J. Giffin, H. Heaslet, A. Brik, Y.-C. Lin, G. Cauvi, C.-H. Wong, D. E. McRee, J. H. Elder, C. D. Stout and B. E. Torbett, *J. Med. Chem.*, 2008, **51**, 6263.

6 (*a*) F. Reck, F. Zhou, M. Girardot, G. Kern, C. J. Eyermann, N. J. Hales, R. R. Ramsay and M. B. Gravestock, *J. Med. Chem.*, 2005, **48**, 499; (*b*) K. Yuldasheva, A. D. Dzhuraev, A. G. Makhsumov and N. Amanov, *Pharm. Chem. J.*, 1991, **25**, 728; (*c*) R. Hanselmann, G. E. Job, G. Johnson, R. Lou, J. G. Martynow and M. M. Reeve, *Org. Process Res. Dev.*, 2010, **14**, 152; (*d*) O. A. Phillips, E. E. Udo, A. A. M. Ali and S. M. Samuel, *Bioorg. Med. Chem.*, 2005, **13**, 4113.

7 (*a*) W.-T. Li, W.-H. Wu, C.-H. Tang, R. Tai and S.-T. Chen, *ACS Comb. Sci.*, 2011, **13**, 72; (*b*) A. Trabocchi, G. Menchi, N. Cini, F. Bianchini, S. Raspanti, A. Bottoncetti, A. Pupi, L. Calorini and A. Guarna, *J. Med. Chem.*, 2010, **53**, 7119.

8 (*a*) V. Aucagne and D. A. Leigh, *Org. Lett.*, 2006, **8**, 4505; (*b*) M. M. Majireck and S. Weinreb, *J. Org. Chem.*, 2006, **71**, 8680; (*c*) C. W. Tornøe, C. Christensen and M. Meldal, *J. Org. Chem.*, 2002, **67**, 3057; (*d*) D. Yang, N. Fu, Z. Liu, Y. Li and B. Chen, *Synlett*, 2007, **278;** (*e*) B. Sreedhar, P. S. Reddy and V. R. Krishna, *Tetrahedron Lett.*, 2007, **48**, 5831; (*f*) A. E. Cohrt, J. F. Jensen and T. E. Nielsen, *Org. Lett.*, 2010, **12**,

5414; (*g*) Q. Wang, S. Chittaboina and H. N. Barnhill, *Lett. Org. Chem.*, 2005, **2**, 293.

9 (*a*) S. Kamijo, T. Jin, Z. Huo and Y. Yamamoto, *J. Am. Chem. Soc.*, 2002, **125**, 7786; (*b*) J. Kalisiak, K. B. Sharpless and V. V. Fokin, *Org. Lett.*, 2008, **10**, 3171; (*c*) Y. Chen, Y. Liu, J. L. Petersena and X. Shi, *Chem. Commun.*, 2008, 3254; (*d*) X. Wang, L. Zhang, H. Lee, N. Haddad, D. Krishnamurthy and C. H. Senanayake, *Org. Lett.*, 2009, **11**, 5026; (*e*) Y. Liu, W. Yan, Y. Chen, J. L. Petersen and X. Shi, *Org. Lett.*, 2008, **10**, 5389; (*f*) W. Tang and Y. Hu, *Synth. Commun.*, 2006, **36**, 2461.

10 J. Li, Y. Zhang, D. Wang, W. Wang, T. Gao, L. Wang, J. Li, G. Huang and B. Chen, *Synlett*, 2010, 1617.

11 Y. Zhang, X. Li, J. Li, J. Chen, X. Meng, M. Zhao and B. Chen, *Org. Lett.*, 2012, **14**, 26.

12 (*a*) B. M. Choudary, M. L. Kantam, K. V. S. Ranganath, K. Mahender and B. Sreedhar, *J. Am. Chem. Soc.*, 2004, **126**, 3396; (*b*) B. M. Choudary, K. V. S. Ranganath, U. Pal, M. L. Kantam and B. Sreedhar, *J. Am. Chem. Soc.*, 2005, **127**, 13167; (*c*) L. Rout, T. K. Sen and T. Punniyamurthy, *Angew. Chem., Int. Ed.*, 2007, **46**, 5583; (*d*) M. L. Kantam, S. Laha, J. Yadav, B. M. Choudary and B. Sreedhar, *Adv. Synth. Catal.*, 2006, **348**, 867; (*e*) J. Beckers and G. Rothenberg, *Dalton Trans.*, 2008, 6573; (*f*) M. B. Thathagar, J. Beckers and G. Rothenberg, *Adv. Synth. Catal.*, 2003, **345**, 979; (*g*) V. P. Reddy, A. V. Kumar, K. Swapna and K. R. Rao, *Org. Lett.*, 2009, **11**, 1697; (*h*) J. Zhang, Z. Zhang, Y. Wang, X. Zheng and Z. Wang, *Eur. J. Org. Chem.*, 2008, 5112; (*i*) V. P. Reddy, A. V. Kumar, K. Swapna and K. R. Rao, *Org. Lett.*, 2009, **11**, 951.

13 (*a*) G. Pacchioni, *Surf. Rev. Lett.*, 2000, **7**, 277; (*b*) W. D. Knight, K. Clemenger, W. A. de Heer, W. A. M. Saunders, Y. Chou and M. L. Cohen, *Phys. Rev. Lett.*, 1984, **52**, 2141; (*c*) A. Kaldor, D. Cox and M. R. Zakin, *Adv. Chem. Phys.*, 1988, **70**, 211; (*d*) L. D. Pachon, J. H. van Maarseveen and G. Rothenberg, *Adv. Synth. Catal.*, 2005, **347**, 811.

14 For selected reviews, see: (*a*) C. Bolm, J. Legros, J. L. Paih and L. Zani, *Chem. Rev.*, 2004, **104**, 6217; (*b*) S. Enthaler, K. Junge and M. Beller, *Angew. Chem., Int. Ed.*, 2008, **47**, 3317; (*c*) A. Correa, O. Garcia Mancheno and C. Bolm, *Chem. Soc. Rev.*, 2008, **37**, 1108; (*d*) B. Plietker, *Iron Catalysis in Organic Chemistry*, Wiley-VCH, Weinheim, Germany, 2008; (*e*) C.-L. Sun, B.-J. Li and Z.-J. Shi, *Chem. Rev.*, 2011, **111**, 1293.

15 For selected examples, see: (*a*) R. B. Bedford, D. W. Bruce, R. M. Frost, J. W. Goodby and M. Hird, *Chem. Commun.*, 2004, 2822; (*b*) R. B. Bedford, D. W. Bruce, R. M. Frost and M. Hird, *Chem. Commun.*, 2005, 4161; (*c*) S. L. Buchwald and C. Bolm, *Angew. Chem., Int. Ed.*, 2009, **48**, 5586; (*d*) J. Fan, L. Gao and Z. Wang, *Chem. Commun.*, 2009, 5021; (*e*) K. Swapna, A. V. Kumar, V. P. Reddy and K. R. Rao, *J. Org. Chem.*, 2009, **74**, 7514; (*f*) Y. Zhang, M. Wang, P. Li and L. Wang, *Org. Lett.*, 2012, **11**, 951.

16 Powder X-ray diffraction spectra's and the SEM-analysis images of the Fe_2O_3 nanoparticles can be found in the ESI†.

