Highly Active and Reusable Cu/C Catalyst for Synthesis of 5-Substituted 1H-Tetrazoles Starting from Aromatic Aldehydes

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Abstract

A new, efficient and convenient method for the synthesis of 5-substituted 1H-tetrazole derivatives with a wide range of substituents in good to excellent yields has been developed. The synthesis was performed by the one-pot three-component [3+2] cycloaddition reaction between aldehyde, hydroxylamine and sodium azide in the presence of Cu/C. The reaction probably proceeds by the in situ formation of nitriles followed by successive [3+2] cycloaddition with sodium azide. A variety of aldehydes were used to obtain the corresponding tetrazoles. The catalyst was recovered by simple filtration and reused at least five times without significant loss of catalytic activity. The use of this method offers additional advantages for the synthesis of 5-substituted 1H-tetrazole derivatives, including the easy availability of starting materials, mild conditions, experimental simplicity and good yields.

Keywords: Heterogeneous catalyst, Cu/C nanoparticle, Tetrazoles, One-pot three component reaction, [3+2] Cycloaddition reaction

1. Introduction

Tetrazoles are a representative class of heterocyclic polyaza compounds, which are extensively investigated due to their broad range of applications. Tetrazoles exhibit potential biological activities such as antibiotic,1 anti-allergic,2 antagonist,3 antihypertensive,4 and antiviral activities.5 These compounds have also been used as an important part of the number of modern drugs.6 More recently, tetrazoles have been used to bind alythiotetrazolylacetanilides with HIV-1 reverse transcriptase.7 In medical chemistry, tetrazoles are considered lipophilic spacers and metabolically stable surrogates for carboxylic acid.8 In addition, tetrazoles have been used in organometallic chemistry as effective stabilizers of metal peptide structures, as peptide chelating agents9,10 and as ligands with different coordination modes in coordination chemistry.11,12 Tetrazoles have also been used as plant growth regulators, herbicides and fungicides.13 In addition, tetrazole compounds are used in photography,14 in specialty explosives15 and in organocatalysis.16

Due to their potential advantages and their wide range of applications, various and new synthesis methods for tetrazoles have been intensively developed.17,18 The [3+2]-cycloaddition of nitriles with sodium azide is known as one of the most conventional methods for the synthesis of 5-substituted 1H-tetrazoles. This reaction was carried out by using catalysts such as copper triflates,19 CdCl2,20 Fe(OAc)2,21 zinc(II) salts,22 AlCl3,23 BF3-OEt2,24 FeCl3-SiO2,25 TBAF,26 4-(N,N-dimethylamino)pyridinium acetate,27 Cu(OAc)2,28 AgNO3,29 CoY zeolites,30 ZnS,31 Cu2O,32 amberlyst 15,33 CuFe2O4 nanoparticles,34 cuttlebone,35 Cu(II) immobilized on Fe3O4@SiO2@L-Arginine36 and Ag/sodium borosilicate nanocomposite.37

In general, toxic and expensive substituted phenylnitriles are used as precursors for the synthesis of tetrazoles. Therefore, the use of more available starting material instead of nitriles and the use of comparatively cheaper and easily accessible catalysts are the two motives that led us to do this work.

Previously, we have reported on copper nanoparticles on charcoal (Cu/C) as an excellent heterogeneous cat-
alyst for the synthesis of triazole, propargylamine, benzimidazole, 2-amino-3-cyanopyridine, indazole and imidazole derivatives.

In continuation of our studies on the synthesis of heterocycles and the use of heterogeneous catalysts in organic reactions, we describe here a new strategy for the preparation of tetrazole derivatives. The strategy is based on a one-pot three-component [3+2] cycloaddition reaction between aldehydes, hydroxylamine hydrochloride and sodium azide using Cu/C as heterogeneous catalyst. The core of our new strategy for the synthesis of tetrazoles is the use of aldehydes instead of nitriles in a tandem process.

2. Experimental Section

2.1. Instrumentation, Analysis and Raw Materials

The NMR spectra were recorded on a Bruker Advance DPX-250 (1H NMR at 250 MHz and 13C NMR at 62.5 MHz) in pure deuterated solvents with tetramethylsilane (TMS) as internal standard. Mass spectra were determined with a Shimadzu GCMS-QP 1000 EX instrument at 70 or 20 eV. Melting points were determined in open capillary tubes in a Buchi-535 melting point device. FT-IR spectroscopy (Shimadzu FT-IR 8300 spectrophotometer) was used to characterize the heterogeneous catalyst. Reaction monitoring was performed by TLC on silica gel Polygram SILG/UV254 plates. Chemical materials were obtained from Fluka, Aldrich and Merck Companies.

2.2. General Procedure

A mixture of aldehyde (1 mmol), hydroxylamine hydrochloride (1 mmol), sodium azide (1 mmol) and catalytic amounts of Cu/C (5 mol%) in DMF (2 ml) was stirred at 120 °C for a reasonable time (Table 2). After completion of the reaction, as indicated by thin layer chromatography (TLC) with n-hexane/ethyl acetate (1:2), the reaction mixture was passed directly through a celite (TLC) with n-hexane/ethyl acetate (1:1) to obtain tetrazoles of high purity.

5-Phenyl-1H-tetrazole (1)

White solid; m.p. 216–217 °C (Lit. 214–216 °C); IR (KBr): δ 3461, 3274, 2926, 2877, 2713, 1600, 1430, 1350, 1237, 1150, 766 cm–1; 1H NMR (250 MHz, DMSO-d6): δ 8.14 (d, 1H, J = 7 Hz); 3.82 (s, 2H); 2.81 (d, 2H, J = 8 Hz); 13C NMR (62.5 MHz, DMSO-d6): δ 128.2, 130.6, 148.7; Anal. calcd. for C9H10N4O2 (204.185): C, 52.94; H, 3.95; found: C, 53.06; H, 4.07.

5-(4-Chloro-phenyl)-1H-tetrazole (4)

White solid; m.p. 250–251 °C (Lit. 249–251 °C); IR (KBr): δ 3433, 3010, 2825, 1516, 1438, 1373, 1054, 824 cm–1; 1H NMR (250 MHz, DMSO-d6): δ 7.68 (d, 2H, J = 8.5 Hz), 8.03 (d, 2H, J = 8 Hz); 13C NMR (62.5 MHz, DMSO-d6): δ 123.1, 128.6, 129.5, 155.2; Anal. calcd. for C9H8N4O2 (180.594): C, 60.66; H, 4.05.

5-(4-Methylphenyl)-1H-tetrazole (5)

White solid; m.p. 280–281 °C (Lit. 248–249 °C); IR (KBr): δ 3478, 3060, 2925, 1516, 1488, 1373, 1304, 1054, 824 cm–1; 1H NMR (250 MHz, DMSO-d6): δ 2.23 (s, 3H); 8.37 (d, 2H, J = 7.6 Hz); 7.90 (d, 2H, J = 7.6 Hz); 13C NMR (62.5 MHz, DMSO-d6): δ 20.9, 121.2, 126.8, 129.8, 141.1, 154.9; Anal. calcd. for C9H8N4 (160.176): C, 59.99; H, 5.03; found: C, 60.08; H, 4.91.

5-(3,5-dimethoxyphenyl)-1H-tetrazole (6)

Brown solid; m.p. 204–205 °C (Lit. 204–205 °C); IR (KBr): δ 3461, 3296, 2926, 2877, 2713, 1600, 1430, 1350, 1237, 1150, 766 cm–1; 1H NMR (250 MHz, DMSO-d6): δ 8.14 (s, 3H), 7.15 (d, 2H, J = 8 Hz), 7.58–7.63 (m, 2H); 13C NMR (62.5 MHz, DMSO-d6): δ 85.5, 110.9, 111.9, 116.1, 120.0, 149.0, 151.0, 154.8; Anal. calcd. for C10H9N4O2 (206.201): C, 52.42; H, 4.89; found: C, 52.29; H, 4.96.

N,N-Dimethyl-4-(1H-tetrazole-5-yl)aniline (7)

White solid; m.p. 250–251 °C (Lit. 249–251 °C); IR (KBr): δ 3433, 3010, 2825, 1516, 1438, 1373, 1054, 824 cm–1; 1H NMR (250 MHz, DMSO-d6): δ 2.23 (s, 3H); 8.37 (d, 2H, J = 7.6 Hz); 7.90 (d, 2H, J = 7.6 Hz); 13C NMR (62.5 MHz, DMSO-d6): δ 20.9, 121.2, 126.8, 129.8, 141.1, 154.9; Anal. calcd. for C9H10N4 (160.176): C, 59.99; H, 5.03; found: C, 60.08; H, 4.91.

4-(1H-tetrazole-5-yl)benzene-1,3-diol (8)

White solid; m.p. 240–241 °C (Lit. 218–220 °C); IR (KBr): δ 3478, 3296, 2926, 2877, 2713, 1600, 1430, 1350, 1237, 1150, 766 cm–1; 1H NMR (250 MHz, DMSO-d6): δ 8.29 (dd, 2H, J1 = 8.8, J2 = 1.8 Hz), 8.43 (d, 1H, J = 8.9 Hz); 13C NMR (62.5 MHz, DMSO-d6): δ 123.7, 124.6, 128.2, 130.6, 148.7; Anal. calcd. for C9H9N4O2 (219.146): C, 43.98; H, 2.64; found: C, 44.09; H, 2.75.
748 cm⁻¹; 1H NMR (250 MHz, DMSO-d₆): δ 6.41 (dd, 1H, J₁ = 8.5, J₂ = 2.3 Hz), 6.47 (d, 1H, J = 2.2 Hz), 7.79 (d, 1H, J = 8.6 Hz), 10.01 (s, 2H); 13C NMR (62.5 MHz, DMSO-d₆): δ 101.7, 102.4, 107.9, 130.0, 151.7, 156.8, 161.2; Anal. calcd. for C₇H₄Cl₂N₄O₂ (178.148): C, 47.19; H, 3.39; found: C, 47.08; H, 3.26.

5-(2-Chloro-phenyl)-1H-tetrazole (9)
White solid; m.p. 178–180 °C (Lit. 175–177 °C). IR (KBr): υ 3286, 1600, 1512, 1460, 1100, 999, 750 cm⁻¹; 1H NMR (250 MHz, DMSO-d₆): δ 7.62 (dd, 1H, J₁ = 8.4, J₂ = 2.0 Hz), 7.82–7.86 (m, 2H). 13C NMR (62.5 MHz, DMSO-d₆): δ 116.8, 118.2, 124.9, 135.4, 138.5, 158.9; Anal. calcd. for C₇H₅ClN₄ (180.594): C, 46.55; H, 2.79; found: C, 46.43; H, 2.68.

5-(1-methyl-1H-pyrrol-2-yl)-1H-tetrazole (12)
White solid; m.p. 240–241 °C (Lit. 244–245 °C). IR (KBr): υ 3286, 1600, 1512, 1460, 1100, 999, 750 cm⁻¹; 1H NMR (250 MHz, DMSO-d₆): δ 8.07 (d, 1H, J = 6.2 Hz), 8.21–8.27 (m, 2H). 13C NMR (62.5MHz, DMSO-d₆): δ 125.8, 126.9, 128.5, 129.2, 154.3; Anal. calcd. for C₇H₄N₄S (152.177): C, 39.46; H, 2.65; found: C, 39.57; H, 2.78.

3. Results and Discussion
The copper nanoparticle on charcoal (Cu/C) as catalyst was synthesized according to our previously published methods (Scheme 1).38

To search for optimal reaction conditions, a three-component reaction model between hydroxylamine hydrochloride, benzaldehyde and NaN₃ was investigated. Different reaction parameters like solvent, temperature, different catalysts and the amount of catalyst were investigated. The corresponding results were summarized in Table 1.

First, different solvents for the preparation of 5-substituted 1H-tetrazole were screened. No product was formed during the reaction in H₂O, CH₃CN and ethanol (Table 1, entries 1–3). In another attempt to synthesize the tetrazole ring, benzaldehyde, hydroxylamine and NaN₃ were used in PEG 200 at 120 °C, which provided the desired tetrazole in very low yield (Table 1, entry 4). When the model reaction was carried out in DMSO at 120 °C, the desired product was obtained in moderate yield as indicated in Table 1, entry 5. The solvent has a noticeable effect in this reaction, in which dimethylformamide (DMF) was the best solvent to achieve the highest yields of the desired tetrazole (Table 1, entry 6).

Next, we investigated the influence of temperature on the model reaction. A temperature increase from 120 to 140 °C had no significant effect on the yield and the reac-
Then the different amounts of catalyst were tested to find the optimum state. The yield was reduced to 68% by reducing the amount of catalyst to 2 mol% (Table 1, entry 10). A further increase in the catalyst quantity did not significantly increase the product yield (Table 1, entry 11). A mixture of aldehyde, hydroxylamine hydrochloride and sodium azide in the absence of Cu/C catalyst was heated to 120 °C for 9 h, but the starting materials were recovered (Table 1, entry 12). To study the catalytic activity of copper, activated carbon was used as a catalyst to reach the target product. The low yield was achieved with activated carbon (Table 1, entry 13). As can be seen from Table 1, the presence of Cu was essential for substrate conversion, and in the absence of Cu, activated carbon did not catalyze the model reaction (entry 13).

To identify the role of Cu/C in this reaction, the catalytic activities of different copper sources were investigated under the same optimal experimental conditions. All alternative copper species produced the desired product in lower yields than Cu/C (Table 2, entries 14–16). Furthermore, separation and reuse of the catalyst was problematic due to its complete dissolution in DMF. The application of this protocol, which is based on the in-situ generation of nitriles, allowed us to efficiently produce tetrazole derivatives.

To determine the generality of this conversion, the reaction of different aldehydes with a multitude of substituents on the aromatic part in the presence of nanocopper on charcoal was investigated. It was found that the reaction is quite general and that it tolerates a large number of

| Table 1. Optimization for the synthesis of tetrazole from aldehyde.* |
|---|---|---|---|---|
| Entry | Solvent | Catalyst (mol%) | Temperature (°C) | Time (h) | Yield (%)b |
| 1 | H2O | Cu/C (5) | Reflux | 9 | – |
| 2 | MeCN | Cu/C (5) | Reflux | 9 | – |
| 3 | EtOH | Cu/C (5) | Reflux | 9 | – |
| 4 | PEG 200 | Cu/C (5) | 120 | 9 | 12 |
| 5 | DMSO | Cu/C (5) | 120 | 9 | 48 |
| 6 | DMF | Cu/C (5) | 120 | 9 | 87 |
| 7 | DMF | Cu/C (5) | 140 | 9 | 89 |
| 8 | DMF | Cu/C (5) | 100 | 9 | 48 |
| 9 | DMF | Cu/C (5) | r.t | 9 | – |
| 10 | DMF | Cu/C (2) | 120 | 9 | 68 |
| 11 | DMF | Cu/C (10) | 120 | 9 | 90 |
| 12 | DMF | – | 120 | 9 | – |
| 13 | DMF | Charcoal | 120 | 9 | 17 |
| 14 | DMF | Cu(OAC)2 (5) | 120 | 9 | 48 |
| 15 | DMF | CuI (5) | 120 | 9 | 53 |
| 16 | DMF | CuSO4 | 120 | 9 | 41 |

* Reaction conditions: benzaldehyde (1 mmol), hydroxylamine hydrochloride (1 mmol), sodium azide (1 mmol) and Cu/C (5 mol%) in solvent (2 mL). b Isolated yields.

| Table 2. Sequential one-pot synthesis of 5-substituted 1H-tetrazoles from aldehydes via in-situ generation of nitriles followed by [2+3] cycloaddition with sodium azide using nano-Cu/C as a catalyst.* |
|---|---|---|---|---|
| Entry | Aldehyde | Product | Time (h) | Yield (%)b |
| 1 | | ![Image 1](https://via.placeholder.com/150) | 9 | 87 |
| 2 | | ![Image 2](https://via.placeholder.com/150) | 9 | 89 |
| 3 | | ![Image 3](https://via.placeholder.com/150) | 15 | 88 |
| 4 | | ![Image 4](https://via.placeholder.com/150) | 9 | 84 |

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substituted benzaldehydes (Table 2). All reactions took place in less than 15 h, and tetrazole derivatives were isolated in good or even high yields (74–89%) without the need to isolate the aryl nitriles as an intermediate. In general, electronic and steric modifications did not have a remarkable effect on the reactivity of the aldehyde.

* Reaction conditions: aldehyde (1 mmol), hydroxylamine hydrochloride (1 mmol), sodium azide (1 mmol) and Cu/C (5 mol%) in DMF (2 mL) at 120 °C. b Isolated yields.
The influence of the withdrawing groups on the aromatic ring of benzaldehyde was also investigated. The reactions with nitro and ester groups were carried out in the isolated yields of 88–89% and the carbonyl functionality remained unaffected (Table 2, entries 2–3).

The [3+2] cycloaddition process was also extended to nitriles with electron donating groups such as methyl, methoxy and N,N-dimethyl. Using the optimal reaction conditions, the corresponding 5-substituted 1H-tetrazoles 5–7 were prepared in 9 h and isolated in good yield (Table 1, entries 5–7).

Benzaldehydes with electron donating groups at the ortho positions of the aromatic rings yielded the corresponding tetrazoles in good yield. However, sterically hindered ortho-substituted benzaldehydes required a longer reaction time (Table 2, entries 8–10).

The above results showed that this reaction can be applied to benzaldehyde for a wide range of functional groups. The reaction proceeded well, regardless of the position and electronic nature of the substituents on the aromatic ring. Next, the reactivity of acid-sensitive heterocyclic aldehydes was investigated. The reaction of furfural, N-methylpyrrole-2-carbaldehyde and thiophene-3-carbaldehyde resulted in the desired tetrazoles 11–13 in good yields (Table 2, entries 11–13).

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To check the reusability of the catalyst, the reaction was carried out with benzaldehyde, hydroxylamine hydrochloride and sodium azide under the optimized reaction conditions. After completion of the reaction, the catalyst was separated from the reaction mixture by simple filtration, washed with ethyl acetate and dried for reuse under air atmosphere. As shown in Figure 1, five recoveries of catalyst were found without significant loss of catalytic activity.

The plausible mechanism for the synthesis of 5-substituted 1H-tetrazoles from aldehydes was shown in Scheme 3 using Cu/C as catalyst. First, oxime is formed on the aldehyde according to the activation of the carbonyl group of the aldehyde and the nucleophilic attack of the aldehyde.
nitrogen atom of the hydroxylamine. In the next step, the nitrile product is formed by splitting off water. Then the nitrile group is activated by Cu/C, which accelerates the cyclization step. The cycloaddition between the nitrile group and the azide ion takes place immediately to form the intermediate product III. After removal of the catalyst by simple filtration and acidic processing, IV and V tautomers are obtained. The more stable tautomer V (5-substituted-1H-tetrazole) is accepted as the significant product.

The efficiency of Cu/C as a catalyst for the synthesis of 5-substituted 1H-tetrazoles starting from aldehydes was compared with that of other catalysts reported in the literature. The results were summarized in Table 3. It is clear that Cu/C is the most effective catalyst for the synthesis of 5-substituted 1H-tetrazole derivatives.

4. Conclusion

In summary, we have developed an efficient direct route for the synthesis of tetrazole derivatives from aromatic aldehydes, hydroxylamine hydrochloride and sodium azide. The reaction was carried out by copper-catalyzed [3+2] cycloaddition to produce 5-substituted 1H-tetrazole in a sequential one-pot three-component reaction without isolation of the nitrile intermediate. The main advantage of this method is the replacement of toxic nitrile precursors by aldehydes. This method demonstrates the potential of the nanocatalyst Cu/C as a very user-friendly, cost-effective and efficient catalyst for the production of 5-substituted 1H-tetrazoles. The catalyst can be easily recovered and reused.

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5. References


Table 3: Comparison between the efficiency of Cu/C as catalyst and some other catalysts for the synthesis of 5-substituted 1H-tetrazole derivatives.
Povzetek