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The Catalytic Activity of Carbon-Supported Cu(I)-Phosphine Complexes for the Microwave-Assisted Synthesis of 1,2,3-Triazoles

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Abstract: A set of Cu(I) complexes with 3,7-diacetyl-1,3,7-triaza-5-phosphabicyclo-[3.3.1]nonane (DAPTA) phosphine ligands viz. $[CuX(\kappa P\text{-DAPTA})_3]$ (**1**: X = Br; **2**: X = I) and $[Cu(\mu\text{-}X)(\kappa P\text{-DAPTA})_2]_2$ (**3**: X = Br; **4**: X = I) were immobilized on activated carbon (AC) and multi-walled carbon nanotubes (CNT), as well as on these materials after surface functionalization. The immobilized copper(I) complexes have shown favorable catalytic activity for the one-pot, microwave-assisted synthesis of 1,2,3-triazoles via the azide-alkyne cycloaddition reaction (CuAAC). The heterogenized systems with a copper loading of only 1.5–1.6% (*w*/*w* relative to carbon), established quantitative conversions after 15 min, at 80 °C, using 0.5 mol% of catalyst loading (relative to benzyl bromide). The most efficient supports concerning heterogenization were CNT treated with nitric acid and NaOH, and involving complexes **2** and **4** (in the same order, **2**_CNT-ox-Na and **4**_CNT-ox-Na). The immobilized catalysts can be recovered and recycled by simple workup and reused up to four consecutive cycles although with loss of activity.

Keywords: Cu(I) complexes; phosphine; DAPTA ligands; carbon nanotubes; click chemistry; CuAAC; triazoles; microwave

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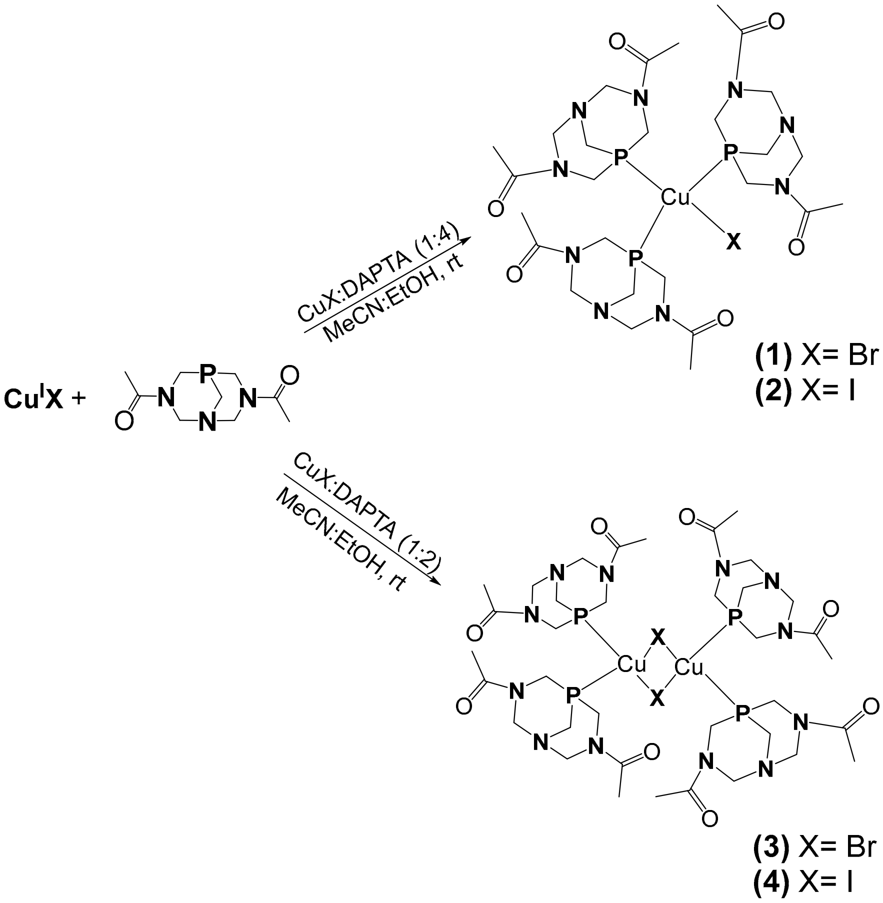
1. Introduction

The interesting properties of 1,2,3-triazole based heterocycles have been a focus of scientific interest due to their manifold potential to interact with diverse systems, not only from a synthetic point of view but also in the context of biological and pharmacological applications [1]. The triazole ring system has been shown to be compatible with many functional groups and to exhibit good stability under several reaction conditions [2].

The copper catalyzed azide−alkyne cycloaddition approach (CuAAC) established by Meldal [3] and Sharpless [4] constitutes the most important protocol to obtain 1,4-disubstituted triazoles in a completely regioselective manner. Enormous efforts have been devoted to maximize the general efficiency of the CuAAC reaction during the last two decades [5,6]. However, the presence of a significant amount of expensive copper complexes in the end products remains a main challenge hampering the utilization of the CuAAC reaction for large scale applications [7,8]. A way to overcome this difficulty is to support the catalyst on solid matrices, a method that was revealed to be effective in achieving more sustainable processes, by preventing not only the accumulation of metal particles, but also the excessive use of reagents [9–11]. By attaching the complex to a solid support, it is possible to efficiently recover and reuse it in consecutive catalytic reactions and improve both catalytic activity and stability [12–14]. Many solid supporting matrices have been successfully utilized for catalytic applications [15,16], among which carbon structures have been privileged due to their high surface area, thermal stability and porous surface [17,18]. Commercially available activated carbon and carbon nanotubes (CNTs) have already been applied as scaffold materials for a variety of metal-based catalysts including copper [19–23].

A significant interest has been directed to the application of transition metal complexes based on the neutral, water-soluble and air-stable 3,7-diacetyl-1,3,7-triaza-5-phosphabicyclo [3.3.1] nonane (DAPTA) ligand in aqueous medium catalysis [24]. In this context, our group has reported the set of copper(I)-DAPTA complexes [CuBr(κP-DAPTA)$_3$] (**1**), [CuI(κP-DAPTA)$_3$] (**2**), [Cu(μ-Br)(κP-DAPTA)$_2$]$_2$ (**3**) and [Cu(μ-I)(κP-DAPTA)$_2$]$_2$ (**4**) (Scheme 1) that demonstrated to be efficient homogeneous catalysts for the microwave-assisted CuAAC reaction [25]. The use of microwave heating, as compared to conventional methods, has been shown to dramatically reduce reaction times, increase product yields and enhance product purity by reducing unwanted side reactions [26–29]. In continuation of our efforts to develop efficient catalytic CuAAC systems [25,30–32] compounds **1–4** were heterogenized in carbon materials (AC and CNT) and utilized as heterogeneous catalysts for the microwave-assisted synthesis of triazoles. The catalytic potential of the supported species are compared with the previously studied homogeneous counterparts [25].



Scheme 1. Synthesis of Cu(I)-DAPTA complexes. Adapted from [25] with permission from The Royal Society of Chemistry.

2. Results and Discussion

2.1. Characterization of the Carbon Materials

The carbon materials used were the commercially purchased AC and CNT. They were subjected to chemical treatments in order to modify the nature and concentration of the surface functional groups. Surface modification was done by nitric acid treatment, by the addition of 5 M HNO_3 and reflux, to give the oxidized AC-ox and CNT-ox materials. These could subsequently be treated with 20 mM NaOH under reflux to produce the AC-ox-Na and CNT-ox-Na carbon supports.

Table 1 shows the BET surface area, pore volume, and pore size of the commercial AC and CNT materials and their treated forms AC-ox, CNT-ox, AC-ox-Na and CNT-ox-Na. Indeed, the treatments have made significant structural modifications to the carbon materials [10,33–37]. In the case of AC there was a significant decrease of the surface area, pore volume and pore size. Nitric acid treatment has been proved to be effective for the creation of surface oxygen-containing functionalities such as carboxylic groups which could inhibit the access of N_2 to the micropores [10,33]. The subsequent NaOH treatment (AC-ox-Na) further reduced the surface area of the material. For CNTs, having a cylindrical structure and the pores result from the free space in the bundles, and the acid treatment opens the CNT end tips (as seen for CNT-ox). Surface oxygen functionalities such as carboxylic groups can be introduced on the outer and possibly the inner walls which result in the formation of edges and steps on the graphene sheets [9,38]. The oxidant effectively opened the carbon nanotubes, and aggregation of the individual CNTs results in a lower value of pore volume and size than in the untreated sample [10,39,40]. Subsequent NaOH treatment (to achieve CNT-ox-Na) appeared not to revert the effect since the essential features were still present at the end of the treatment.

Table 1. Characterization of carbon materials using BET analysis.

Carbon Material	S_{BET}, $m^2\ g^{-1}$	Pore Volume, $cm^3\ g^{-1}$	Pore Size, nm
AC	866	0.45	5.2
AC-ox	223	0.22	5.0
AC-ox-Na	191	0.15	4.9
CNT	256	2.54	30.9
CNT-ox	288	1.37	17.4
CNT-ox-Na	253	1.16	16.3

2.2. Heterogenization Efficiency

The copper compounds **1–4** were heterogenized on the six carbon materials in attempts to obtain ~2% Cu. The surface treatments were proved to provide significant structural modifications on the carbon supports and to enhance the immobilization process. Anchoring of the metal-containing species to the carbon materials was done by the wet impregnation method, whereby a solution containing the precursor of the active phase (the copper complex) is contacted with the solid support. The suspension was continuously stirred for 24 h, after which the solid was separated by filtration and dried to remove the absorbed solvent.

As shown in Table 2, the different treatments affect the porous structure and surface chemistry of the supports, but the obtained materials were able to anchor the Cu complexes, although with different efficiencies. Heterogenization of the complexes was better observed in the ox-Na supports, followed by the -ox and the least effective were the original materials. This suggests that the increase in the number of surface groups brought by the treatments acts as a scaffold that increases the capacity of the complex to anchor effectively. The formation of phenolate and carboxylate groups obtained with the -ox-Na treatment can probably explain the higher heterogenization levels considering that these groups might act as coordination sites for the copper complexes [11,14]. Possible coordination and other interacting modes of Cu(I)-phosphine complexes onto the carbon materials are shown in Figures S10–S13. They can involve replacement of the halo (X) ligand by a carboxylate or phenolate group of the carbon matrix (Figure S10), addition of one of these groups to the Cu atom (Figure S11), or a non-covalent interaction such as H-bonding (Figure S12) or ionic interaction (Figure S13).

Table 2. Metal loading of Cu on the carbon materials [a].

Carbon Material	**Cu Complex**							
	1		**2**		**3**		**4**	
	g/L	**%**	**g/L**	**%**	**g/L**	**%**	**g/L**	**%**
AC	0.01	0.1	0.02	0.3	0	0	0.01	0.1
AC-ox	0.07	0.9	0.06	0.8	0.05	0.6	0.04	0.5
AC-ox-Na	0.11	1.5	0.11	1.5	0.09	1.2	0.12	1.6
CNT	0	0	0.01	0.1	0	0	0	0
CNT-ox	0.06	0.8	0.02	0.3	0.03	0.4	0	0
CNT-ox-Na	0.06	0.8	0.11	1.5	0.06	0.8	0.10	1.3

[a] Values obtained from ICP analysis.

The nature of the surface groups and the immobilization of the copper complexes were further investigated using FTIR spectroscopy. Figures S7–S9 show the corresponding FTIR spectra of the CNT-ox-Na support and the heterogenized complexes **2** and **4**, respectively. The presence of the peak at ~1720 cm^{-1} is related to C=O carboxylate group vibrations from the HNO_3 treatment to increase the functionalization of the nanotubes. These functional groups are usually found attached to the ends of the nanotubes due to the enhanced reactivity of these areas [41]. By comparing the FTIR spectra before and after heterogenization, an observed shift in the peak of the carbonyl group from 1631 cm^{-1} to 1613 and 1618 cm^{-1} could be related to the chemical bond formed between the carboxylate group and Cu^+ [42,43]. The peak at ~1400–1450 cm^{-1}, present in the heterogenized samples but not on the support, suggests that there is O–H bending deformation in carboxylic and phenolic groups while the peak at ~1160–1200 cm^{-1} may be associated with the C–O stretching in the same functionalities [44]. Hence, these observations may indicate that the Cu(I)-phosphine complex is immobilized on CNT-ox-Na support via interactions between the terminal carboxylate groups on the surface of CNT-ox-Na.

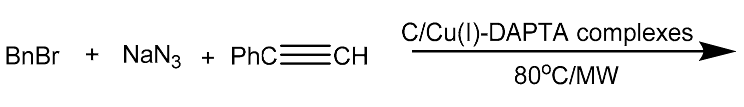
The main advantages of the immobilization technique include the absence of any complication in the heterogenization process, the widespread availability of carbon materials, the lack of any tedious procedure to alter the catalyst to facilitate the immobilization, the rapidity and experimental simplicity of the methodology by which heterogenization can be completed.

2.3. Microwave-Assisted One-Pot Synthesis of 1,2,3-Triazoles

To exploit the activity of the Cu complexes **1–4** immobilized on the different carbon materials, the solid systems were used as catalysts for the one-pot synthesis of 1,4-disubstituted-1,2,3-triazoles.

The reaction of benzyl bromide, sodium azide and phenylacetylene was chosen as model (Table 3). The heterogenized materials with 1.2–1.6% Cu loadings (see Table 2) were tested as catalysts for this reaction. The initial experimental conditions included a catalyst loading of 0.5% (relative to benzyl bromide), the temperature of 80 °C, 1.5 mL of H_2O:MeCN 1:1 solvent mixture, 30 W microwave (MW) irradiation and a reaction time of 15 min (Table 3, entries 1–8). Raising the temperature to the previously chosen value of 125 °C for the homogeneous systems [25] did not significantly improve the results (Table 3, entries 9–14). Different reaction times, catalyst loadings, and volumes of solvent were then screened to determine the optimum reaction conditions (Table 3, entries 15–24).

Table 3. The 1,3-dipolar azide-alkyne cycloaddition catalyzed by Cu(I)-DAPTA complexes (**1–4**) anchored on different carbon supports [a].



Entry	Complex	Support	Catalyst Loading [b], mol%	Time, min	Total Volume of Solvent, mL	Yield [c], %	TON [d]
1	**1**	AC-ox-Na	0.5	15	1.5	30.5	61
2	**2**	AC-ox-Na	0.5	15	1.5	31.4	63
3	**3**	AC-ox-Na	0.5	15	1.5	22	44
4	**4**	AC-ox-Na	0.5	15	1.5	20	39
5	**1**	CNT-ox-Na	0.5	15	1.5	23	46
6	**2**	CNT-ox-Na	0.5	15	1.5	41	82
7	**3**	CNT-ox-Na	0.5	15	1.5	29	59
8	**4**	CNT-ox-Na	0.5	15	1.5	33	66
9	**1**	AC-ox-Na	0.5	15	1.5	27 [e]	54
10	**2**	AC-ox-Na	0.5	15	1.5	32 [e]	65
11	**2**	CNT-ox-Na	0.5	15	1.5	40 [e]	80
12	**3**	AC-ox-Na	0.5	15	1.5	29 [e]	59
13	**4**	AC-ox-Na	0.5	15	1.5	38 [e]	75
14	**4**	CNT-ox-Na	0.5	15	1.5	40 [e]	80
15	**2**	CNT-ox-Na	0.5	30	1.5	29	59
16	**2**	CNT-ox-Na	0.1	15	1.5	21	207
17	**2**	CNT-ox-Na	0.5	15	2.0	32	65
18	**2**	CNT-ox-Na	0.5	30	2.0	27	55
19	**2**	CNT-ox-Na	0.5	15	1.0	17	34
20	**2**	CNT-ox-Na	0.5	30	1.0	23	46
21	**4**	CNT-ox-Na	0.1	30	1.5	23	230
22	**4**	CNT-ox-Na	0.5	30	1.5	25	50
23	**4**	CNT-ox-Na	0.5	60	1.5	42	84
24	**4**	CNT-ox-Na	1.0	15	1.5	48	48

[a] Reaction conditions: benzyl bromide (0.30 mmol), phenylacetylene (0.33 mmol), NaN$_3$ (0.33 mmol), H_2 O: MeCN (1:1 *v/v*), 80 °C. [b] Calculated vs. benzyl bromide. [c] Isolated yield. [d] Turnover number = moles of product per mol of metal content in the catalyst (as obtained from ICP). [e] Reaction temperature: 125 °C.

The product was isolated by extraction with ethyl acetate followed by solvent removal to obtain the solid product. Structural assignments were determined by comparing the ^{1}H- and ^{13}C NMR spectra of the obtained triazole with those reported previously. In particular, the resonance of the proton in the 5-position of the 1,2,3-triazole ring as shown in the ^{1}H NMR spectrum perfectly agrees with literature data [25,42] (see the Supporting Information for details).

According to the data given in Table 3, the catalysts bearing the mononuclear complexes **1** and **2** are more active than those containing the dinuclear compounds **3** and **4** when immobilized on AC-ox-Na support (Table 1, entries 1–4). The substantially lower BET surface area and micropore volume of AC-ox-Na materials in comparison with the others and the bulkiness of the dinuclear compounds could have been possible causes of inaccessibility of the reactants to the active centers resulting in the decreased yields obtained from complexes **3** and **4** on the AC-ox-Na support. However, when the complexes **1–4** were immobilized on the CNT-ox-Na support, those bearing the iodo ligand (**2** and **4**) gave higher product yields regardless of their nuclearity (Table 1, entries 5–8). A plausible justification concerns the higher metal loading of complexes **2** and **4** on the CNT-ox-Na support (shown in Table 2) which eventually can result from a higher lability of the Cu-I bond (than that of Cu-Br) which would be favorable to the immobilization of the catalyst on this support or to the accessibility of the reagents to the metal centers upon iodo-ligand displacement. A related finding was observed with NHC-complexes [(NHC)CuX] (NHC = N-heterocyclic carbene; X = Cl, Br, I), as catalysts for CuAAC reaction with the general trend iodine> bromine> chlorine [45]. This can be accounted for by the formation, in the catalytic cycle, of copper-acetylide and -acetylide-azide intermediate species that requires the replacement of labile co-ligands [46].

Among the carbon materials used as support, the CNT-Ox-Na (Table 3, entries 6 and 8) gave the most satisfactory yields. Regardless of the type of carbon support being used for **2** (Table 3, entries 2 and 6) the yields (31.4% and 41%) and TONs (63 and 82) are higher than those obtained homogeneously (26% and TON of 52) [25] under identical experimental conditions.

Significant effects of attaching the catalytic complex to a solid support include confinement, site-isolation, prevention of dimerization, cooperative effect of support, among others [47]. The presence of phenolate and carboxylate surface groups, due to the -ox-Na treatment, might explain the increased conversion since these moieties act as a scaffold for the complexes to anchor effectively [9–14].

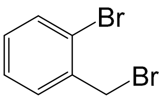
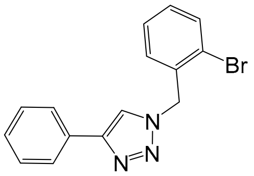
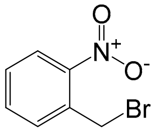
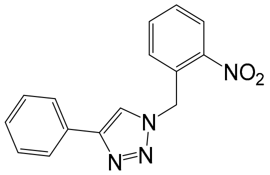
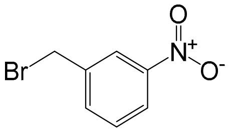
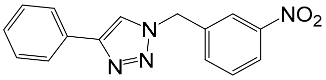
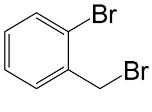
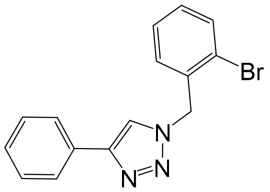
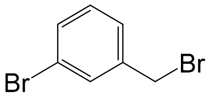
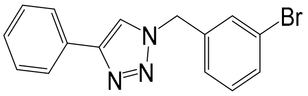
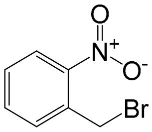
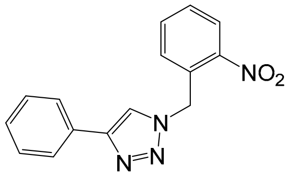
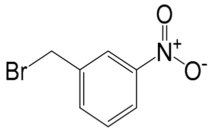
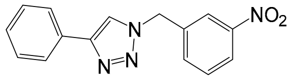
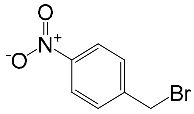
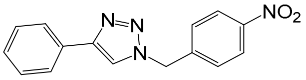
The CNT materials gave the most satisfactory yields among the supports. Possible reasons might be due to the nature and concentration of surface functional groups, the absence of porosity for easy access to the active centers by the reactants, or an electronic effect caused by the graphitic structure of CNT that can lead to enhanced interactions with the reactants or intermediate radicals [9,14].

Since the CNT-ox-Na anchored complexes **2** and **4** (hereafter denoted as **2**_CNT-ox-Na and **4**_CNT-ox-Na) gave the highest yields for the CuAAC reaction under the initial experimental conditions (Table 3, entries 6 and 8), they were further used to explore the effect of variation of other experimental factors i.e., catalyst loading, irradiation time, and total volume of solvent. In the case of **2**_CNT-ox-Na, an increase in both the total volume of solvent and irradiation time (Table 3, entry 18) dropped the yield to 27%. A drop in yield to 21% or to 17% was observed when the catalyst loading or the solvent volume was decreased (Table 3, entries 16 and 19, respectively). The solvent effect in the reaction yield may be tentatively explained by substrate-solvent interactions and concentration effects. Decreasing the solvent volume to 1.0 mL gave a poor yield possibly due to the low solubility of the reactants with partial precipitation, while increasing to 2.0 mL would dilute the reaction mixture and eventually hinder the interaction between substrates, with a decrease in the kinetics of the reaction. With **4**_CNT-ox-Na, the yield significantly improved to 42% when the irradiation time was increased to 60 min (Table 3, entry 23), and to 48% when the catalyst loading was set to 1.0 mol% (Table 3, entry 24). Further increases of catalyst loading were not explored since it would defeat the TON values and the purpose of doing away with stoichiometric excess of expensive catalysts, which is one of the main fundamentals of heterogenization.

To investigate the generality and versatility of **2**_CNT-ox-Na and **4**_CNT-ox-Na as catalysts for the CuAAC reaction to furnish the triazole derivatives, we explored the effect of substituted benzyl bromides using the aforementioned optimized experimental conditions (Table 3, entries 6 and 23). The results are shown in Table 4.

The effect of the benzyl substituents on the yield of the reaction depended on the catalyst. With **2**_CNT-ox-Na the use of 2-bromobenzyl bromide instead of the non-substituted aromatic substrate decreased the yield of the corresponding triazole product (compare entry 1 in Table 4 with entry 6 in Table 3). However, when nitrobenzyl bromides were used, the yields increased regardless of the substituent position (*ortho* or *meta*) in the aromatic ring (Table 4, entries 2–3). The opposite was observed for catalyst **4**_CNT-ox-Na (Table 4, entries 4–8): when 2-bromobenzyl bromide was used the yield increased from 48% (Table 3, entry 22) to 51% (Table 4, entry 4), but with 3-bromobenzyl bromide it decreased to 37% (Table 4, entry 5); with the nitro group, a stronger electron-withdrawing moiety, the obtained yields of product dropped with a decreasing trend conceivably following the *ortho* > *meta* > *para* group position (Table 4, entries 6–8). Further details on the characterization of compounds can be found in the Supporting Information.

Table 4. Synthesis of triazoles using phenylacetylene and substituted benzyl bromides [a].

Entry	Catalyst	Benzyl Bromide	Product	Time, min	Yield [b], %	TON
1	**2**_CNT-ox-Na			15	38	76
2	**2**_CNT-ox-Na			15	48	97
3	**2**_CNT-ox-Na			15	49	98
4	**4**_CNT-ox-Na			60	51	101
5	**4**_CNT-ox-Na			60	37	74
6	**4**_CNT-ox-Na			60	39	79
7	**4**_CNT-ox-Na			60	37	74
8	**4**_CNT-ox-Na			60	32	64

[a] Reaction conditions: benzyl bromide (0.30 mmol), phenylacetylene (0.33 mmol), NaN_3 (0.33 mmol), H_2O: MeCN (1.5 mL, 1:1 *v*/*v*), 80 °C, 0.5 mol% of catalysts (**2**_CNT-ox-Na and **4**_CNT-ox-Na) vs. benzyl bromide derivatives. [b] Isolated yield.

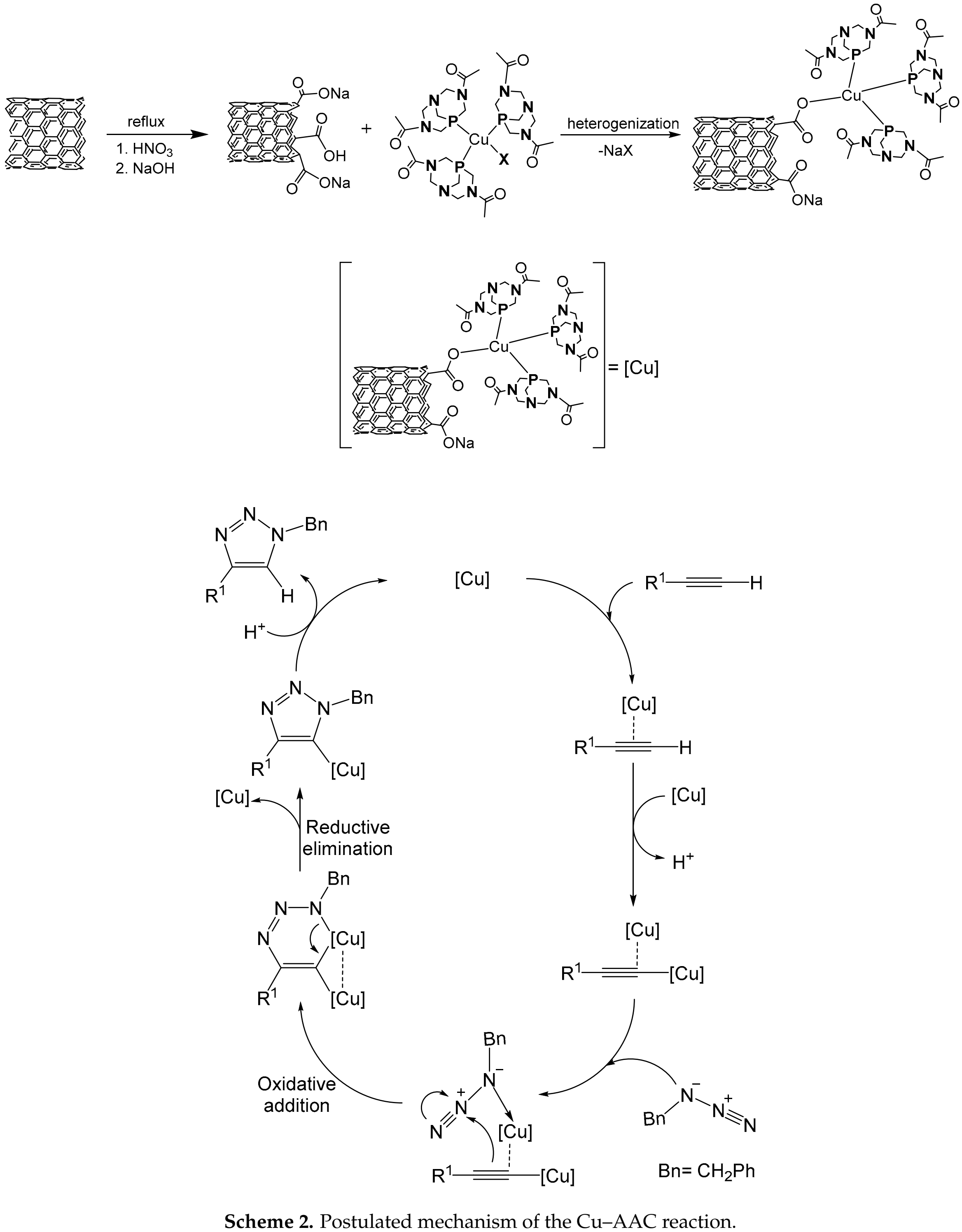
The 1,3-dipolar cycloaddition is a well-known reaction that can be catalyzed by heterogeneous copper metal such as copper nanoparticles, nanoclusters, or copper wire [7]. Carbon nanomaterials with immobilized copper complexes based on *N*-heterocyclic carbenes (NHC) have been reported as recyclable catalysts for CuAAC reactions by Nia et al. [48]. Specifically, Cu(I) nanoparticles immobilized on CNT only achieved a 30% conversion with 2–5 mol% catalyst loading at 40 °C for 96 h. Yields improved to 60% with an 8 mol% catalyst loading for 24 h reaction time. Nasrollahzadeh et al. [49] prepared a heterogeneous catalyst consisting of copper nanoparticles on amorphous carbon to be used for the click reaction to synthesize 1,2,3-triazoles. Despite the long reaction time of 4 h, the best result gave the product with a yield of 97%, obtained with 1.0 mmol of starting materials with a catalyst loading of 0.5 mol% at 70 °C. Hosseinzadeh et al. [50] employed $Cu(OAc)_2$/MCM-41 (Mobil Composition of Matter No.41) catalyst for the one-pot synthesis of 1,2,3-triazoles in water. The optimum product yield of 98% was achieved at 90 °C for 15 min. Yet, the need for 45 mol% sodium ascorbate as reducing agent for Cu(II) to Cu(I) makes it an unattractive procedure. Shargi et al. [42] attempted to immobilize copper nanoparticles on charcoal for the multicomponent catalytic synthesis of 1,2,3-triazole derivatives. The use of 1 mol% of Cu/C in water as catalyst for the CuAAC reaction, furnished the 1,4-disubstituted triazole product in 91% yield after stirring for 45 min at 100 °C. Although the catalyst loading was low, the metal loading used for Cu/C was found to contain ~10% (*w*/*w*) of Cu based on ICP analysis [42].

Despite the numerous publications on the heterogeneous copper-catalyzed azide-alkyne coupling reaction, the carbon-supported Cu-DAPTA complexes with a copper loading of only 1.5–1.6% immobilized on the carbon materials were able to establish quantitative conversions, which were obtained at a shorter reaction time of 15 min, a lower temperature of 80 °C, a lower catalyst loading of 0.5 mol%, and no additional reducing agent.

A proposed mechanism for the CuAAC reaction is depicted in Scheme 2, based on several studies that have been reported toward its elucidation [51,52]. Subsequent kinetic experiments [53] and theoretical investigations [54,55] have been carried out leading basically to similar qualitative conclusions that reflect the up-to-date understanding of this reaction. In the first step of the mechanism, a terminal alkyne binds to a copper(I) center as a π-ligand. This coordination increases the acidity of the alkyne terminal proton, hence a stable σ,π-di(copper) acetylide complex can be formed upon deprotonation [31,56]. The reaction of azide replaces one of the ligands and binds reversibly to the copper atom via the nitrogen proximal to carbon, forming a bridging dicopper μ-acetylide intermediate [53,57]. Subsequently, the distal nitrogen of the azide attacks the C-2 carbon of the acetylide forming an intermediate six-membered cupracycle [58]. The next step involves reductive ring contraction to afford the triazolide intermediate. The last step corresponds to a fast protonation of the copper(I) triazolide leading to the release of the triazole product and the active copper species catalyst is regenerated, thereby completing the catalytic cycle.

By attaching the catalytic complex to a solid support, it is possible to efficiently recover the catalyst to be used for further catalytic cycles. The recyclabilities of **2**_CNT-ox-Na and **4**_CNT-ox-Na were explored for up to 4 consecutive cycles (Figures 1 and 2). On completion of each stage, the triazole product was analyzed and the heterogenized solid catalyst was recovered by filtration, washed thoroughly with distilled water, and dried overnight. The subsequent cycle was initiated upon the addition of new standard portions of all other reagents. As shown in Figures 1 and 2, the yields and corresponding TON values decrease in each successive cycle, conceivably due to leaching of the catalyst from the support. Indeed, the triazole functionality of the product of the azide-alkyne click reaction has a strong complexing ability for Cu catalyst and can compete with the solid support. Hence, this release-recapture reaction mechanism could invoke some leaching and explain the decrease in the yield [7].

The **2**_CNT-ox-Na recyclability is limited but still represents a considerable progress in view of the *ca.*19% yield obtained after the 4th cycle, as compared to only a value of 5.1% yield achieved after the 4th recycling process of complex **2** working homogeneously as a catalyst for the CuAAC reaction [25].



Scheme 2. Postulated mechanism of the Cu–AAC reaction.

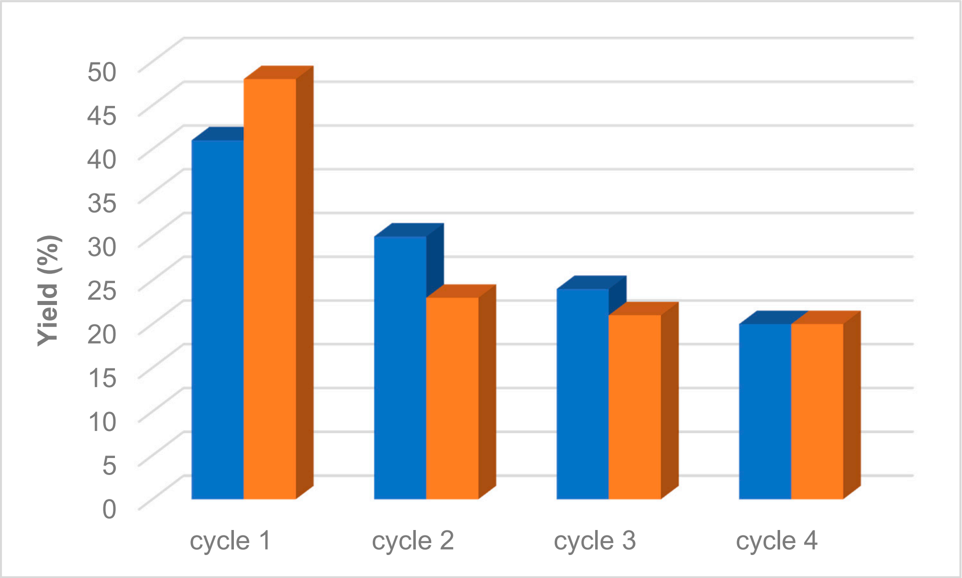


Figure 1. Effect of catalyst recycling on the yield of the product for the MW-assisted synthesis of 1,2,3-triazole catalyzed by **2**_CNT-ox-Na (🟦) and **4**_CNT-ox-Na (🟧). Reaction conditions: 0.5 mol% of **2**_CNT-ox-Na vs. benzyl bromide, 1.0 mol% of **4**_CNT-ox-Na vs. benzyl bromide, 15 min, 30 W microwave irradiation, 80 °C.

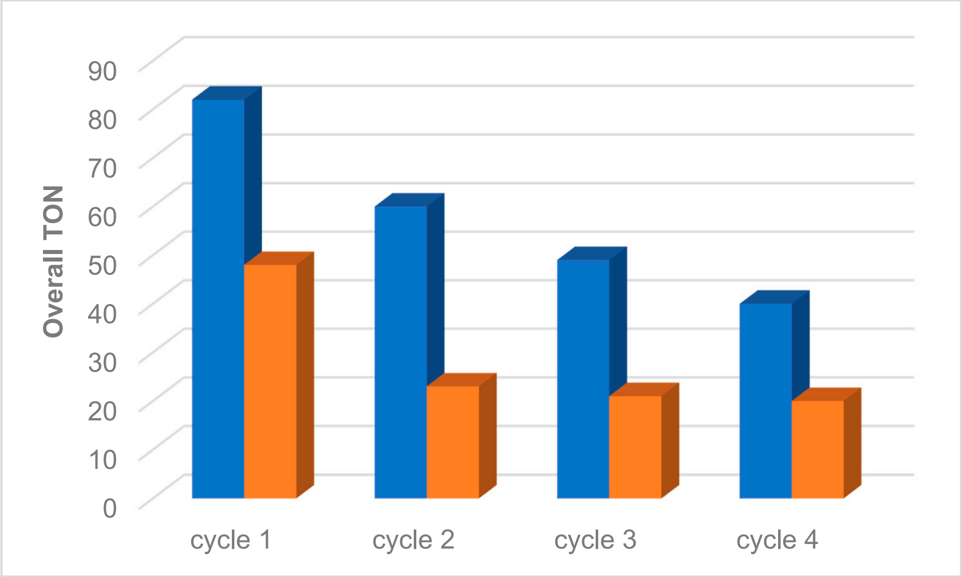


Figure 2. Effect of catalyst recycling on the overall TON of the product for the MW-assisted synthesis of 1,2,3-triazole catalyzed by **2**_CNT-ox-Na (🟦) and **4**_CNT-ox-Na (🟧). Reaction conditions: 0.5 mol% of **2**_CNT-ox-Na vs. benzyl bromide, 1.0 mol% of **4**_CNT-ox-Na vs. benzyl bromide, 15 min, 30 W microwave irradiation, 80 °C.

3. Materials and Methods

3.1. General Procedures

All procedures were performed in air. Reagents and solvents were obtained from commercial sources and used without further purification. Infrared spectra (4000–400 cm^{-1}) were recorded on a Vertex 70 (Bruker) instrument in KBr pellets. ^{1}H, ^{13}C and DEPT NMR spectra were obtained using Bruker Avance II 300 MHz and 400 MHz spectrometers at ambient temperature. The chemical shifts were reported in ppm using tetramethylsilane as an internal reference. Electrospray mass (ESI-MS) spectra were obtained on a Varian 500-MS LC Ion Trap Mass Spectrometer equipped with an electrospray ion source. The compounds were observed and reported in the positive mode (capillary voltage = 80–105 V).

The microwave irradiation was done using the Anton Paar Monowave 300 microwave reactor. The loading of Cu on the carbon materials was determined by Inductively Coupled Plasma (ICP) at the Laboratório de Análises of Instituto Superior Técnico. The carbon materials were characterized by N_2 adsorption at 77 K in Micrometrics ASAP 2060 gas sorption instrument. Materials were previously degassed at 150 °C for 48 h. The multipoint Brunauer–Emmett–Teller (BET) theory and the t-plot method procedure were used for estimating the total and the external surface areas of the materials. The complexes [CuBr(κP-DAPTA)$_3$] (**1**), [CuI(κP-DAPTA)$_3$] (**2**), [Cu(μ-Br)(κP-DAPTA)$_2$]$_2$ (**3**) and [Cu(μ-I)(κP-DAPTA)$_2$]$_2$ (**4**) were prepared according to the literature methods [25].

3.2. Treatments of the Carbon Materials

Two different carbon materials were employed as starting supporting matrices, activated carbon (AC) and multi-walled carbon nanotubes (CNT), used as such or subjected to surface treatments. These included oxidation by refluxing for 3 h 1 g of carbon in 75 mL of a 5 M HNO_3 solution, followed by filtration and washing with distilled water until neutral pH [9,11,12,37,59,60] in this way, the AC-ox and CNT-ox supports were obtained. When AC-ox or CNT-ox were mixed with 75 mL of a 20 mM NaOH solution, refluxed for 1 h followed by filtration and washing with distilled water until neutral pH [10–13,37,47,59–61], the set of AC-ox-Na and CNT-ox-Na supports were attained. In this way, a total of six different carbon materials were used in the work.

3.3. Heterogenization Protocol

Immobilization of complexes **1–4** on the carbon supports was carried out by dissolving a calculated amount of each complex in 20 mL of a 1:1 (*v*/*v*) H_2O:MeCN solvent mixture and, subsequently, 0.15 g of the carbon material were added so as to achieve 2 wt% Cu per mass of carbon. The mixture was stirred continuously for 24h and then filtered, washed with water, and dried overnight at 120 °C.

3.4. Catalytic Essays

In a typical procedure, a tightly capped 10 mL borosilicate glass vial equipped with a magnetic stir bar and containing the heterogenized catalysts (0.5 mol% relative to benzyl bromide), benzyl bromide (0.30 mmol), phenylacetylene (0.33 mmol), and NaN_3 (0.33 mmol, 0.0215 g) in 1.5 mL of the solvent mixture (H_2O:MeCN, 1:1 *v*/*v*), was placed in a microwave reactor. This was stirred (600 rpm) and simultaneously irradiated (30 W) for 15 min at 80 °C. After the set reaction time, the mixture was allowed to cool at room temperature and two phases were observed. After extraction with ethyl acetate, the organic phase was collected and taken to dryness to afford the corresponding triazole product; it was washed with petroleum ether and no further purification step was performed. The heterogenized catalyst was separated by filtration, washed with water, oven-dried, and reused as suitable.

4. Conclusions

A simple and reproducible synthetic method for recyclable heterogeneous catalysts based on Cu(I)-DAPTA complexes (**1–4**) on carbon materials (AC and CNT) was developed. The carbon nanotubes treated with nitric acid and NaOH (CNT-ox-Na) provided the most effective support concerning heterogenization. The treatments with HNO_3 and NaOH have modified the nature and concentration of surface functional groups of the carbon solid support. The total surface area of all materials was reduced by NaOH treatment and the surface modification brought by ox-Na surface oxidation was favorable in terms of catalytic activity.

It is noteworthy that all the reactions were done without using an inert atmosphere. The immobilized iodo-Cu(I)-DAPTA complexes **2** and **4** on CNT-ox-Na affording the **2**_CNT-ox-Na and **4**_CNT-ox-Na supports have shown particularly favorable catalytic activity for the multicomponent synthesis of 1,2,3-triazoles, which can eventually relate to a higher lability of the Cu-I bond. The conditions and yields of the heterogenized systems with a copper loading of only 1.5–1.6% (*w/w*) concern a promising route to establish quantitative conversions obtained at 15 min, 80 °C, 0.5 mol% catalyst loading. Furthermore, the process avoids the isolation of organic azides and affords the products without tedious purification steps. The **2**_CNT-ox-Na and **4**_CNT-ox-Na can be recovered and recycled by simple filtration of the reaction solution and reused for up to four consecutive cycles.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4344/11/2/185/s1, Characterization NMR data and spectra of the triazoles, Figure S1: ESI-MS$^+$ spectrum of 1-benzyl-4-phenyl-1H-1,2,3-triazole, Figure S2: ESI-MS$^+$ spectrum of bromobenzyl-4-phenyl-1H-1,2,3-triazole, Figure S3: ESI-MS$^+$ spectrum of nitrobenzyl-4-phenyl-1H-1,2,3-triazole, Figure S4: FTIR spectrum of 1-benzyl-4-phenyl-1H-1,2,3-triazole, Figure S5: FTIR spectrum of bromobenzyl-4-phenyl-1H-1,2,3-triazole, Figure S6: FTIR spectrum of nitrobenzyl-4-phenyl-1H-1,2,3-triazole, Figure S7: FTIR spectrum of CNT-ox-Na support (2000-400 cm^{-1}), Figure S8: FTIR spectrum of **2**_CNT-ox-Na (2000-400 cm-1), Figure S9: FTIR spectrum of **4**_CNT-ox-Na (2000-400 cm^{-1}), Figure S10: Coordination at the Cu centre through a carboxylate group upon replacement of an iodo ligand, Figure S11: Coordination at the Cu centre through a carboxylate or a phenolate group, Figure S12: Via hydrogen bonding from a carboxylic or a phenolic group, Figure S13: Via ionic interactions.

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