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Carbocatalysed Oxidative C_{sp^2}–C_{sp^2} Homocouplings of Benzo-Fused Heterocycles

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Abstract: Appropriate and fine-tuned treatments of amorphous carbon (AC) involving *aqua regia* or concentrated HNO_3 lead to oxidised carbon materials (oAC) which are able to catalyse 2,2′- and 3,3′-homocouplings of various functionalised indoles with outstanding activity. This newly developed carbocatalysed C_{sp^2}–C_{sp^2} bond formation can be achieved under mild thermal conditions. The study on the scope of the reaction revealed that the reaction can be extended to the homocoupling of other substrates of high synthetic interest such as 2-naphthol, 2-functionalised benzofurans and benzothiofurans. The characterisation of oAC with XPS together with *ad hoc* experiments aimed at blocking the active site revealed that the presence and distribution of C=O functionalities is critical and correlates well with the catalytic activity. Such experiments provide solid support for elucidation of the mechanism, suggesting a quinone nature of the active C=O groups, which are spontaneously regenerated by oxygen. This is confirmed by the fact that 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) is able to promote the coupling in a stoichiometric fashion.

Keywords: biindoles; carbocatalysis; heterogeneous catalysis; homocoupling; oxidative dehydrogenative coupling

Introduction

One of the major challenges in contemporary catalysis development is to discover environmentally benign materials and processes that preferably are earth abundant, renewable and recyclable while the process itself should operate in an atom economic and waste-free fashion under mild conditions. From this perspective the recent emergence of oxidative catalysis by carbon-based materials has received a lot of attention.[1] Particularly, oxidative carbocatalysis that utilises atmospheric oxygen as a terminal oxidant has a potential to replace many oxidative processes that are traditionally performed by transition metals or with stoichiometric oxidative reagents.

The use of heterogeneous carbon-based catalysts, even unprocessed carbon materials, such as active carbon (AC), has been particularly investigated in the oxidative dehydrogenation (ODH) of hydrocarbons, and even, for example, in the conversion of 9,10-dihydroanthracene to anthracene or indoline to indole aromatisation.[2] For this class of reactions, a remarkably higher catalytic activity can be achieved if the AC is oxidised. For instance, dehydrogenation of ethylbenzene to styrene by oAC catalysts has been shown to proceed very efficiently.[3] The recent emergence of carbocatalysis largely relies on a wide range of redox and acid-base reactions catalysed by graphene-based materials.[1] Among these, graphene oxides (GO) have been shown to be efficient catalysts in a number of oxidations.[4] However, the only reported ODH reaction for GO is the sparing conversion of isobutane to isobutene.[5] In addition, more sophisticated carbon nanomaterials,[6] like carbon nanotubes (CNT) and oxidised carbon nanotubes (oCNT), have been shown to be effective in ODH of but(a/e)ne to butadiene and ethylbenzene to styrene.[7,8] To attain high ODH activity, a high abundance of carbonyl/quinone groups on carbon materials is of vital importance as Su, Schlögl, Müllen and co-workers have strongly implicated in the ethylbenzene dehydrogenation by the phenanthrenequinone cyclotrimer.[9] Although the class of ODH has enjoyed a decent level of development, not many reports are available on other organic reactions catalysed by heterogeneous carbon materials.

Most of the carbocatalytic quinone-mediated ODH reactions that have been studied are essentially gas phase reactions. In the liquid phase some very demanding oxidations have been performed, for example, N-doped CNTs are able to oxidise cyclohexane to cyclohexanol, cyclohexanone and adipic acid.[10] Undoped CNTs have been used as a catalyst in similarly difficult oxidations of benzene to phenol utilising H_2O_2 as terminal oxidant.[11] However, in both of these cases carbonyl/quinone groups have not been described to contribute to the catalytic activity and in the former case they have even been found to be detrimental. Beyond oxidations, some other interesting GO-catalysed organic transformations have been reported in the liquid phase, such as hydration of alkynes to ketones,[12] Friedel–Crafts addition of indole to unsaturated ketones[13] or dehydration of xylose to furfural,[14] yet they proceed principally *via* acid catalysis.[1b]

In our previous report, we developed a heterogeneous gold catalyst for the cyclisation of 2-alkenylanilines to indoles. As a serendipitous discovery, we observed that some of the cyclised indoles further homocoupled to afford the corresponding 3,3′-biindoles *via* C−C bond formation when heated in toluene with the carbon supported catalyst.[15] The heterogeneous gold was prepared by immobilising an *aqua regia* solution of $HAuCl_4$ to the AC support with the incipient wetness method. Subsequently, we discovered that even the *aqua regia* treated support without gold is able to catalyse the homocoupling reaction. Undoubtedly, the acid treatment oxidised the AC to some degree, and thus, it became catalytically active, now being able to oxidatively homocouple indoles through $C_{sp^2}-C_{sp^2}$ bond formation.

In this update, we report an in-depth study of the biindole formation by oAC catalysts, we extended the substrate scope to other benzo-fused heterocycles,[16] optimised the reaction conditions, and identified the catalytically active functional group, which in turn allowed us to consider the possible mechanism for the homocoupling. To the best of our knowledge, this is the first reported oxidative $C_{sp^2}-C_{sp^2}$ coupling catalysed by a metal-free carbon-only support, which could open new doors in the more sustainable utilisation of heterogeneous metal-free carbon-based catalysts in more sophisticated syntheses of organic molecules of synthetic and industrial interest.

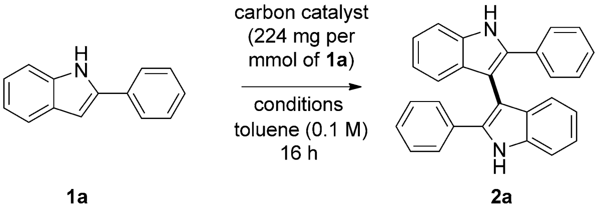
Results and Discussion

Screening of Conditions

After the initial finding,[15] we began to study the carbocatalytic homocoupling by screening different reaction conditions, oxidative acid treatments and carbon materials using commercially available 2-phenylindole as substrate with 16 h reaction time (Table 1, entries 1–11). At first, we tested different conditions for *aqua regia*-treated, oxidised active carbon (oAC) (entries 1–6). Higher yields of the product were realised at elevated temperatures, 10%, 22%, 37% and 51% at 23 °C, 50 °C, 70 °C and 90 °C, respectively (Table 1, entries 3–6). The use of an oxygen atmosphere improved notably the yields, although the reaction still proceeded to some extent even in an argon atmosphere (entries 1–3). Interestingly, the yield rose to 87% and 92% when oAC was prepared with concentrated HNO_3 (entries 7 and 8) from NORIT-pellets or from G-60 carbon powder, respectively.

In order to study how the other known ODH carbocatalysts perform compared to the oAC material, we tested the catalytic performance of oxidised carbon nanotubes (oCNT) with the model reaction as

Table 1. Screening of reaction conditions and catalysts.



Entry	Catalyst	Treatment	Temp. [°C]	Atmosphere	Yield[a] [%]
1	G-60	*aqua regia*	90	Ar	24
2	G-60	*aqua regia*	90	air	35
3	G-60	*aqua regia*	90	O_2	51
4	G-60	*aqua regia*	23	O_2	10
5	G-60	*aqua regia*	50	O_2	22
6	G-60	*aqua regia*	70	O_2	37
7	NORIT	HNO_3	90	O_2	87
8	**G-60[b]**	**HNO_3**	**90**	**O_2**	**92**
9	oCNT-1[b]	HNO_3:H_2SO_4 (3:1)	90	O_2	60
10	oCNT-2[b]	HNO_3:H_2O_2 (3:1)	90	O_2	9
11	oCNT-3[b]	HNO_3	90	O_2	54
12	G-60	–	90	O_2	26
13	–	–	90	O_2	–

[a] Yields determined with ^{1}H NMR using 1,3,5-trimethoxybenzene as an internal standard.
[b] See preparation in the Supporting Information.

they have been reported to catalyse various ODH reactions.[1]

In the case of oCNT the catalytic activity also turned out to be dependent upon the oxidation treatment employed (Table 1, entries 9–11). The best performing catalyst (oCNT-1) was prepared *via* a very aggressive treatment with mixtures of HNO_3:H_2SO_4 which likely introduces a higher fraction of oxygen-containing functionalities, including ketones, which are essential for the catalysis. It is known that the edges of oCNTs contain ketonic C═O groups that have been suggested to cause the observed activity in the ODH reaction of butane.[6] Catalyst oCNT-3 exhibits a lower albeit good activity, while upon H_2SO_4:H_2O_2 treatment (oCNT-2), the activity found is much lower, and this may be related to the higher content of peroxide groups introduced on the CNT by this treatment, which may be detrimental for catalysis. Moreover, it highlights the importance of HNO_3 in the oxidation treatment. The best activity for nanotubes, however, is substantially lower than that of the best G-60 catalyst. This may be partially due to the lower surface area exhibited by the oCNTs as reported in the literature[17] as compared to the G-60.

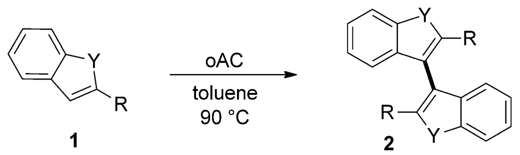
Notably, a reference test with non-oxidised G-60 under optimised conditions, that is, at 90 °C, under an O_2 atmosphere, yielded 26% of the product (entry 12). In our previous study we have analysed the G-60 AC with ICP-MS and discovered only ppm amounts of metals that could potentially be responsible for the catalysis. Doping the catalyst with 0.2% of the most abundant metal impurity (Fe 378 ppm) did not increase the yield (see the Supporting Information).[15] Without oAC no reaction was observed under these conditions (entry 13).

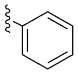
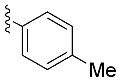
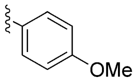
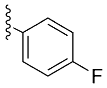
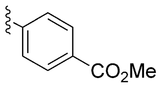
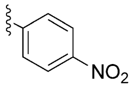
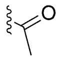
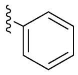
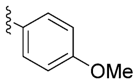
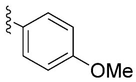
Scope of the Reaction

With a well performing catalyst in our hands, we then pursued to study the scope of the reaction. We were delighted to obtain numerous 2-aryl-substituted 3,3′-biindoles in good to excellent yields as products (Table 2, entries 1–9). The reaction was found to be applicable to the synthesis of both electron-withdrawing (NO_2, CO_2Me) and electron-donating (Me, OMe) substituted, *para* functionalised 2-aryl-3,3′-biindoles (Table 2, entries 1–6). In line with our previous study,[15] the coupling proceeded smoothly in the case of electron-donating substituents on the aromatic ring whereas reactions of electronegative substituents required higher catalyst loadings and longer reaction times. Also, *N*-methyl-2-phenylindole was homocoupled to biindole, which indicates that the indole NH proton is not critical for the coupling (entry 9).

Phenyl substituents could also be replaced by aliphatic substituents such as ethoxy ester or methyl ketone but in these cases prolonged reaction times and increased catalyst loadings were required (Table 2, entries 7 and 8). Perhaps not surprisingly, use of 2-(3,3-dimethybut-1-yn-1-yl)indole as a starting material yielded not the homocoupling product but led to formation of the corresponding ketone in 24% yield. This is in agreement with the carbocatalysed alkyne hydrations reported in studies carried out with GO.[1,18]

Table 2. Study of the scope of the reaction with several benzo-fused heterocycles catalyzed by additive-free oAC.



Entry	Comp.	Y	R	n[a]	Time [h]	Molarity [M]	Yield[b] [%]
1	**1a**	NH		1	16	0.1	79
2	**1b**	NH		1	44	0.1	91
3	**1c**	NH		1	16	0.1	84
4	**1d**	NH		1	49	0.1	75
5	**1e**	NH		2.5	45	0.25	91
6	**1g**	NH		5	29	0.25	68
7	**1f**	NH	CO_2Et	5	96	0.25	44
8	**1h**	NH		5	185	0.25	14
9	**1i**	NMe		2.5	24	0.25	61
10	**1j**	O		5	22	0.25	39
11	**1k**	S		5	89	0.25	27

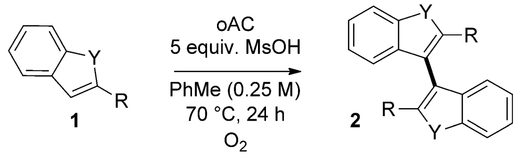
[a] Carbocatalyst was used n * 224 mg per mmol of SM.
[b] Isolated yields after column chromatography.

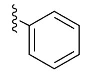
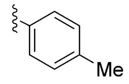
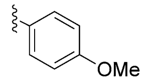
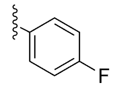
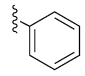
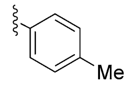
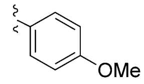
We then moved to study if the reaction is applicable to the dimerisation of different benzo-fused heterocycles (furans and thiophenes) as these substructures are found in natural products,[19] in organic chiral electrodes[20] and in diphosphine ligands.[21] However, under the optimised indole–indole homocoupling conditions, the reaction was only applicable to the coupling of electron rich 2-(4-methoxyphenyl)-substituted benzofuran and benzothiophene with low isolated yields (Table 2, entries 10 and 11).

At this point we reasoned that an acid additive could boost the oxidative processes by oAC in a similar manner as stoichiometric oxidative couplings with 2,3-dichloro-5,6-dicyano-1,4-quinone (DDQ) benefit from the addition of an acid.[22] Pleasingly, after adding 5 equivalents of methanesulfonic acid to the reaction mixture we were able to obtain 3,3′-bibenzofurans and 3,3′-bibenzothiophenes from good to excellent isolated yields at lower temperatures (Table 3, entries 1–7). Again, without oAC, no reaction was observed with the MsOH additive.

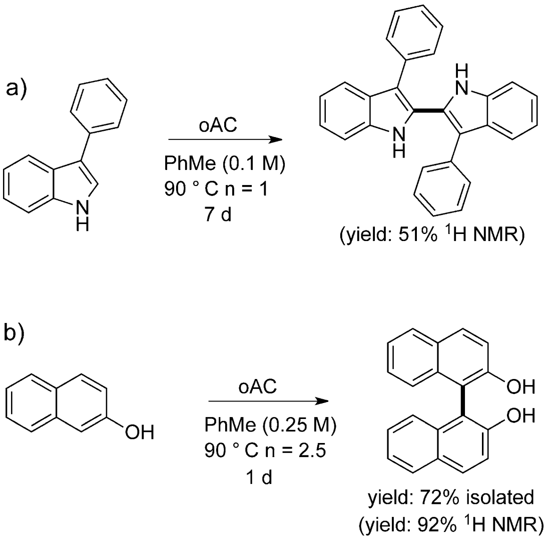
Beyond the 3,3′-couplings of benzo-fused heterocycles, we demonstrated with 3-phenylindole that the corresponding 2,2′-heterocoupling is also feasible by the oAC catalysis (Scheme 1a).

Table 3. Study of the scope of the reaction with several benzo-fused furan and thiophene heterocycles by acid-additive oAC catalysis.[a]



Entry	Comp.	Y	R	n[a]	Yield[b] [%]
1	**1l**	O		5	63[c]
2	**1m**	O		5	83
3	**1j**	O		5	86
4	**1n**	O		5	69
5	**1o**	S		5	76
6	**1p**	S		5	98
7	**1k**	S		5	95

[a] Carbocatalyst was used n * 224 mg per mmol of SM.
[b] Isolated yields after column chromatography.
[c] Average of two runs



Scheme 1. Synthesis of a) 2,2′-biindole and b) 1,1′-bi-2-naphthol (BINOL) catalyzed by oAC.

Noteworthy, we could apply the same coupling reaction to non-heterocyclic molecules such as 2-naphthol. Hence, upon running the experiment under the standard catalytic conditions, we were pleased to obtain binaphthol in 92% yield (NMR) after 24 h (Scheme 1b). This is a finding of paramount importance as it implies that upon fine-tuning of the conditions, we can considerably expand the applicability range to other molecules of biological interest or use it in natural product synthetic steps. In this case without the catalyst no reaction takes place under the catalytic conditions. The binaphthol itself is not stable under the reaction conditions and only 62% of it was isolated when subjected to reaction conditions.

Another aspect that would be of exceptional value is to apply the above studied reaction in benzo-fused heterocouplings. Unfortunately, attempts to selectively catalyse heterocouplings between two different indoles failed, yielding mainly statistical mixtures of homo- and heterocoupled products (see the Supporting Information, Figure S1).

As rather large loadings are needed to run the catalysis effortlessly, the recyclability of the oAC catalysts becomes highly relevant from an applicability point of view. Our recycling tests with 1.5 h reaction time show (Figure 1) that the catalyst efficiency drops by 20% from 48% to 28% after the first cycle but in the following cycles the activity decreases by only 7% being still 21% on the fifth cycle. Instead, when the catalyst is regenerated with *aqua regia* after the first cycle only 9% of the activity is lost compared to the loss of 20% without regeneration. The reason for this significant deactivation after the first cycle is currently under further study. However, a similar decay of activity is observed after heating treatment (*vide infra*).

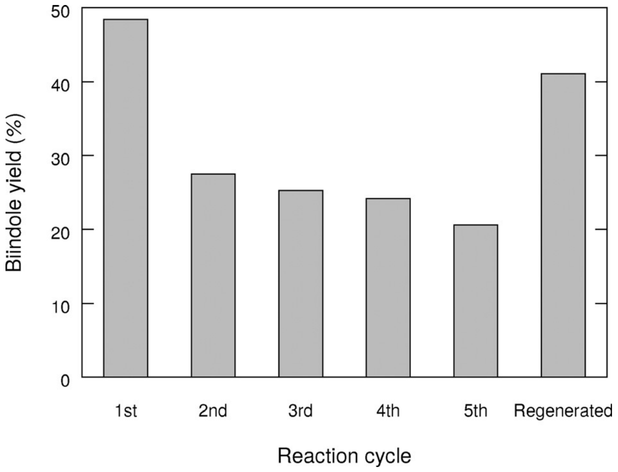


Figure 1. Recycling of oAC in the homocoupling reaction of **1a** to afford **2a** with 1.5 h reaction time.

Determination of Active Site and Characterisation of Catalyst

In several reported carbocatalyst studies both benzoic acid and carbonyl/quinone functional groups have been identified to be critical for the observed catalytic activity.[2–6] In order to trace the active site of the oAC catalyst, we prepared two series of catalysts with either successive *aqua regia* treatments or with different nitric acid concentrations to study the effect of the degree of oxidation on the catalytic activity (Figure 2).

We then characterised the functional groups in both catalyst series with X-ray photoelectron spectroscopy (XPS) and observed a clear correlation between the relative amount of carbonyl (C=O) groups and the yield of the reaction (Figure 3a). Not surprisingly, carboxylic/lactone (O−C=O) groups are also formed in the catalyst preparation but the relative amount of them did not correlate with the activity of the catalyst (Figure 3b).

For a further characterisation a ^{13}C solid state NMR spectrum was recorded and notably a broad signal at 165 ppm was detected (Supporting Information, Figure S8). If attributed to a carbonyl resonance (C=O), the shift falls at unusually high fields; however, if assigned to a quinone functionality and integrated in electron-deficient carbon material, the shielding could be well explained. Previously, during characterisation of GO material, a similar broad signal at 167 ppm has been suggested to arise from a carbonyl group.[23] To check whether this resonance could originate instead from CO_2H groups, we removed these groups by heating oAC for 18 h at 400 °C under nitrogen,[24] thereafter the ^{13}C NMR spectrum was measured again and only a trace of the original signal could be detected indicating that the 167 ppm resonance was likely produced by a CO_2H carbon (Supporting Information, Figure S8). After the heating treatment the catalytic activity was observed to decay to 60% of that of the original oAC. Notably, this decay is of comparable magnitude with the one that was observed after the first catalytic cycle in the recycling experiments above. This can be interpreted in that the untreated and non-recycled catalyst has some loosely bound group(s) that give(s) a contribution to the homocoupling reaction.

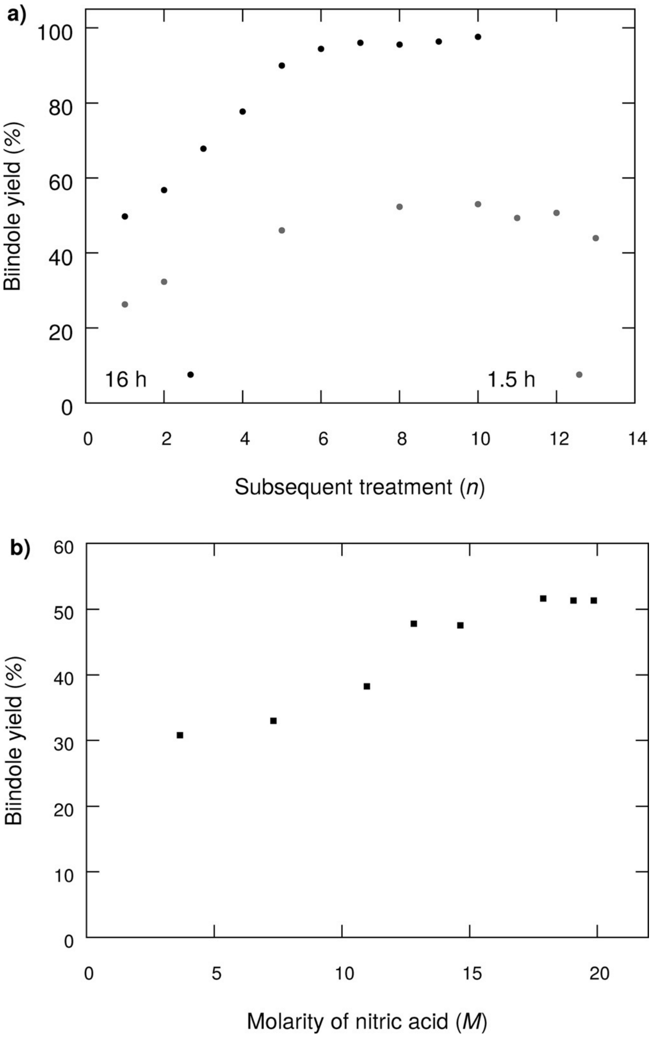


Figure 2. Monitoring of indole **1a** to biindole **2a** homocoupling with oAC catalyst prepared a) by successive *aqua regia* treatments with reaction times of 1.5 and 16 h; and b) by varying the concentration of HNO_3 after 1.5 h reaction time.

To elucidate the role of surface area and porosity, BET surface areas and pore volumes of AC, oAC and once used oAC were analysed for the G-60 carbons (Supporting Information, Figure S3 and Figure S4). Pristine AC is known to be a highly porous material with a large surface area. Nonetheless, various oxidising treatments are known to alter the properties of AC by changing pore structures and surface area.[25] The amended pore volumes and sizes could lead to

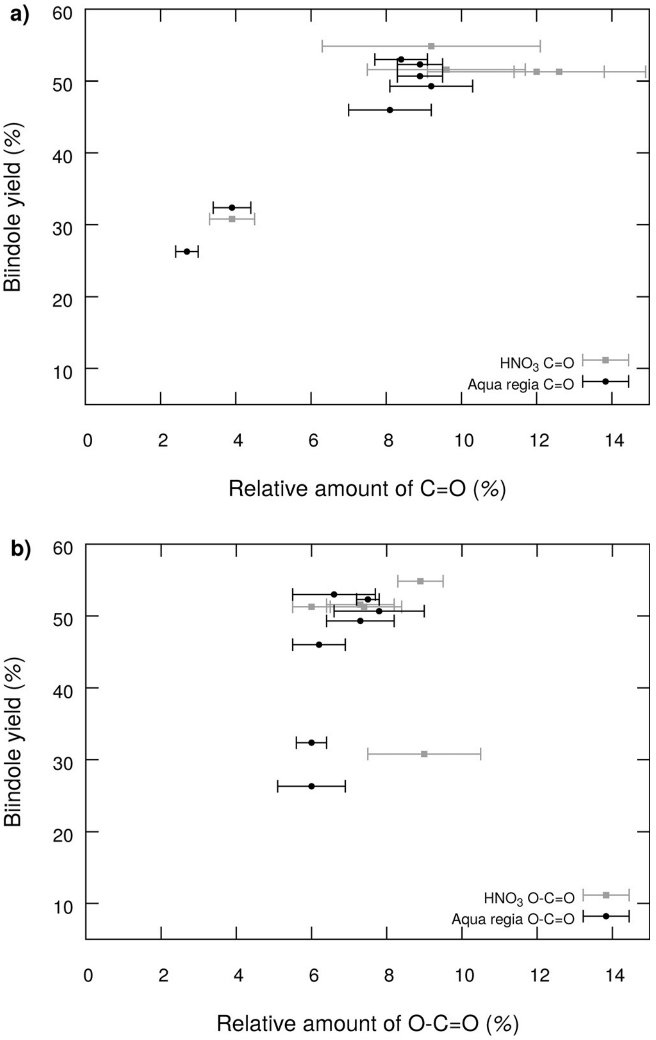


Figure 3. Relative amounts of C=O (a) and O–C=O (b) groups versus **1a**→**2a** homocoupling yield, determined with XPS and ^{1}H NMR, respectively.

enhanced or diminished catalytic activity. Meanwhile, the surface area might also play a role, especially, if the reactive sites are evenly distributed on the surface.

The BET analysis revealed that the nitric acid treatment, i.e., conversion of AC to oAC, caused some substantial material erosion; diminishing clearly both the surface area and micropore volumes. For a once used catalyst both the area and volumes were further reduced. An analogous inspection of meso- and macropore volumes reveals that they are similarly decreased after oxidation (Supporting Information, Figure S4), but slightly increased after one reaction cycle. Interestingly, when the decrease of micropore volume after one reaction cycle is compared to that of the concurringly reduced catalytic activity, both changes are of a similar magnitude, being 43% and 35%, respectively.

Next, the oAC (Table 1, entry 8) was analysed with thermogravimetry (TGA) which indicated that the amount of oxygen functionalities relative to the carbon is 11% (Supporting Information, Figure S7) while XPS measurements suggest that this ratio is 18.5%. We interpret that the observed gap arises from the fact that a larger amount of the functional groups are located on the surface of oAC and the XPS as a surface sensitive technique detects predominantly this area. Also, as the weight loss in the TGA experiment is progressive and it does not occur with clear-cut steps, making a very accurate calculation difficult.

In order to gain additional evidence on the active site, we selectively blocked C=O, CO_2H and OH groups one by one with a procedure that was recently developed by Su and co-workers.[26] The derivatisation of carboxylic acids with bromoacetophenone to esters or esterifying the phenolic functionalities with benzoic acid anhydride did not have any notable effect on the yield (Figure 4). In stark contrast to this, the reaction was completely inhibited when the carbonyls were blocked with phenylhydrazine, giving further insight to the identity of the active site.

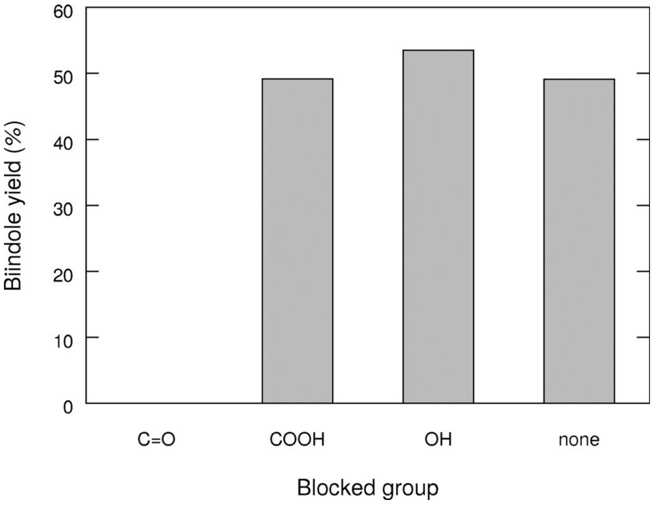


Figure 4. Effect of chemical blocking of functional groups on the oAC on the biindole yield.

The structural similarity between oAC's presumed active site and certain organic quinone-type oxidants inspired us to conduct a control experiment using DDQ as a reagent. In the case of 2-arylindoles unknown mixtures of products were obtained but satisfyingly 2-arylbenzofurans could be homocoupled with DDQ in the presence of an acid co-catalyst (Figure 5).[27] We reason that a co-catalyst is needed due to the higher oxidation potential of benzo- and thiofurans than indoles.

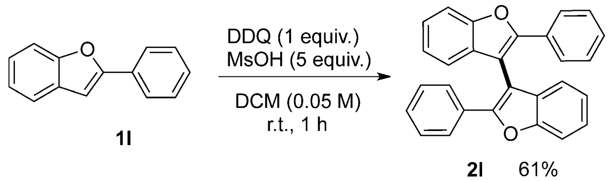


Figure 5. Homocoupling of benzofuran **1l** to 3,3′-bibenzofuran **2l** by DDQ in the presence of acid.[27]

Reaction Mechanism

In our previous studies an addition of the radical 4-oxo-(2,2,6,6-tetramethylpiperidin-1-yl)-oxy (oxo-TEMPO) inhibited the homocoupling indicating a radical character for the studied reaction.[15] In the literature there is a plethora of oxidative dehydrogenative aromatic couplings which operate through a radical mechanism in the presence of either Lewis or Brønsted acids.[28] In relation to this, the characterisation of oAC shows that there are both quinone type C=O and acidic CO_2H groups on the carbon material. Although the acid groups were not necessary for the indole homocouplings, the benzofuran homocoupling can also be mediated either with DDQ or oAC as an oxidant in the presence of MsOH additive. Hence, it is probable that also the mechanisms of these analogous oxidative couplings resemble each other. In this comparison an obvious difference is that the oAC is regenerated by oxygen, which can be thought as a separate process from a mechanistic perspective. An additional dissimilarity of the carbon material is that it seems to be less electrophilic which allows the use of nucleophilic indoles as substrates.[29]

Thus, based on the literature, we have reasoned that the homocouplings on oAC may proceed *via* two probable pathways (Figure 6). The first one is initiated with single electron transfer (SET), i.e., oxidation of benzoheterocycle **I** to the radical cation **Ia**, which is then coupled to neutral hererocycle **I** (Figure 6a). The formed dimer **IIa** is a distonic radical cation[30] and it is further oxidised to dication **IIIa**. The product **IV** is generated from the dication **IIIa** after elimination of two protons. The second envisioned mechanistic route begins with a hydrogen atom abstraction, or alternatively with a consecutive SET and deprotonation. The SOMO of the neutral radical **Ib** is strongly localised at the heterocycle 3-position (Figure 6b) and forms radical dimer **IIb** with neutral heterocycle **I**. The intermediate is then further oxidised and deprotonated to form a neutral homocoupling product **IV**. At present, we think that the former, pathway A, is more likely, especially when an acid additive is used to assist the homocoupling reaction. Both mechanisms are being experimentally and computationally studied and the results will be published elsewhere in due course of time.

Conclusions

The current study indisputably shows that the oAC is capable to catalyse oxidative $C_{sp^2}-C_{sp^2}$ bond formation as demonstrated with various examples of dimerisation of the 2-substituted benzo-fused heterocycles with good to excellent isolated yields. The XPS and chemical blocking experiments indicate that the developed oAC material contains a substantial abun-

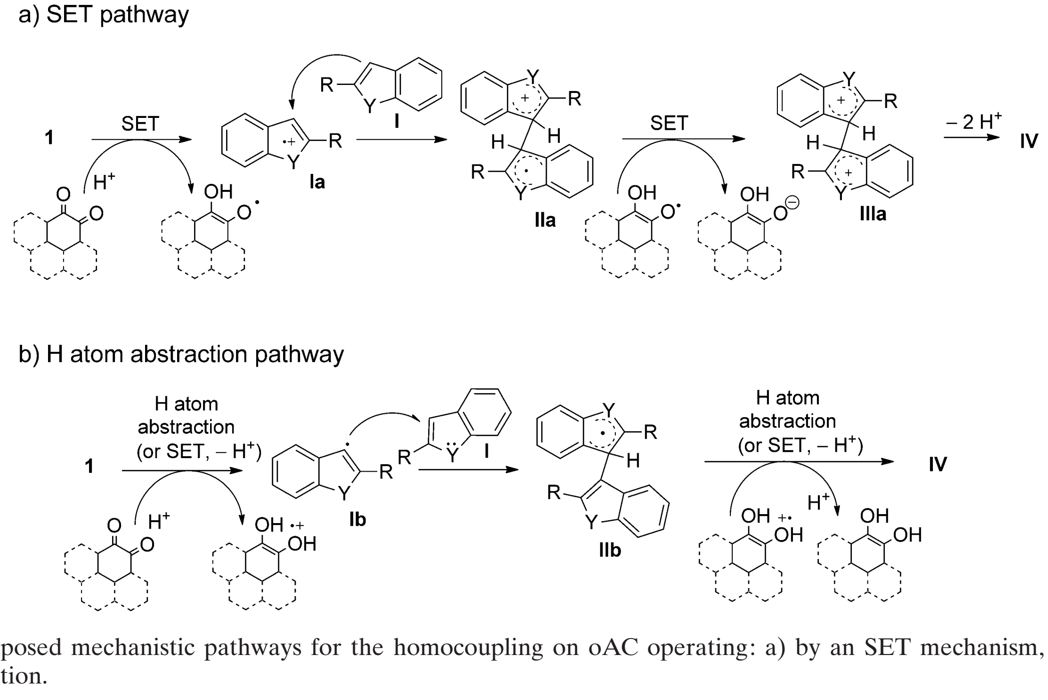


Figure 6. Proposed mechanistic pathways for the homocoupling on oAC operating: a) by an SET mechanism, and b) by H atom abstraction.

dance of ketone C=O groups, evidently forming quinone-like moieties, which are chiefly responsible for the revealed catalytic redox activity of the carbon material. Obviously, the coupling mechanism on the carbocatalyst is an analogue to that of DDQ, which is capable to homocouple (2-aryl)benzofurans in a stoichiometric fashion, whereas on the carbon material the hydroquinone-type moieties are regenerated to corresponding quinones by O_2 as terminal oxidant. There is also a mechanistic similarity to the ODH mechanism suggested for ethylbenzene/styrene conversion by oCNT catalysis. However, there is one factor (i.e., the dramatic 40% activity decay after the first cycle) which we cannot rationally explain at this stage and that deserves further studies.

Substantial advantages for oAC material are its easy preparation from inexpensively available active carbon, its simple recyclability or optional reactivation. It can be reasonably expected that the developed oAC can be applied to a variety of oxidative conversions. As a final remark we note that when oxidative acids, like HNO_3, are used in the incipient wetness method to immobilise metals or nanoparticles on carbon support, the formed functional groups on the carbon material might not only bind the metal ions,[31] but also show some oxidative catalytic activity as such.

Experimental Section

oAC Catalyst Preparation (Entry 8, Table 1)

Activated charcoal (DARCO© ~100 mesh particle size, powder; LOT #MKBQ5057V, obtained from Sigma–Aldrich) (AC) was stirred in 70 °C with 1 M hydrochloric acid ($8.0\ \mathrm{mL\,g_{AC}}^{-1}$) for 6 h to remove metal impurities. AC was filtered and washed with 30 × 100 mL of water and dried in an oven at 140 °C for 17 h. Acid washed AC was then oxidised with HNO_3. The nitric acid was added dropwise to the AC and the formed mixture was constantly stirred with a glass rod. Acid was added until a paste was formed indicating filling of the pores of AC ($2.6\ \mathrm{mL\,g_{AC}}^{-1}$). Heating (140 °C, 16 h) was started after the addition of the acid was finished. In a typical set-up a round-bottomed flask was connected to an empty Drechsler-bottle which was fitted with a PVC-tube with a funnel in the other end. The funnel end of the tube was submerged in dilute NaOH solution. After 16 h heating at 140 °C the Drechsler bottle was filled with water and vacuum (water aspirator) was applied to the mixture for 2 h at 140 °C to dry the catalyst (see picture 1 in the Supporting Information).

Homocoupling without Additive

General procedure (GP 1) for homocoupling without additive: Starting material and HNO_3-treated activated carbon ($224\ \mathrm{mg\,mmol^{-1}} \times n$) were weighted to a flask and the atmosphere was exchanged to O_2 by three successive vacuum–O_2 cycles. Toluene was added to the mixture and the mixture was stirred at the given temperature for a given time. The reaction mixture was then filtered through a pad of diatomaceous earth and washed with acetone (**2a**–**2h**) or chloroform (**2i**). Purification of the crude material by flash chromatography (SiO_2) using hexane and ethyl acetate or toluene as eluent yielded the final product.

Following the **GP 1** with 50 mg (0.259 mmol) of indole (**1a**), 58 mg of HNO_3-treated activated carbon ($n = 1$), 2.56 mL of PhMe (0.1 M) were used with 16 h reaction time. Purification of the crude with 5:1→3:1 (hexane:ethyl acetate) afforded **2a** as a yellowish solid; yield: (39.1 mg (0.102 mmol, 79%). ^{1}H NMR (500 MHz, acetone): $\delta = 10.68$ (s, 2H), 7.58 (d, $J = 7.5$ Hz, 4H), 7.51 (d, $J = 8.3$ Hz, 2H), 7.18–7.07 (m, 10H), 6.91 (t, $J = 7.5$ Hz, 2H).

Homocoupling with MsOH Additive

General procedure (GP 2) for homocoupling with MsOH additive: Starting material and HNO_3-treated activated carbon ($224\ \mathrm{mg\,mmol^{-1}} \times n$) were weighed to a flask and the atmosphere was exchanged to O_2 by three successive vacuum–O_2 cycles. Toluene was added to the mixture followed by MsOH (5 equiv.) and the mixture was stirred at 70 °C. After 24 h the reaction mixture was filtered through a pad of diatomaceous earth and basic Al_2O_3. The filter cake was washed with chloroform. Purification of the crude by flash chromatography (SiO_2) using hexane and ethyl acetate as eluent yielded the final product.

Following the **GP 2** with 48.3 mg (0.249 mmol) of benzofuran (**1l**), 278.4 mg of HNO_3-treated activated carbon ($n = 5$), 119.6 mg (80.8 μL) of MsOH, and 1.0 mL of PhMe (0.25 M) were used. Purification of the crude material with 1:0→40:1 (hexane:ethyl acetate) afforded **2l** as an off white solid; yield: 32.8 mg (0.0847 mmol, 68%). ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 7.77$–7.74 (m, 4H), 7.62 (d, $J = 8.3$ Hz, 2H), 7.34–7.30 (m, 2H), 7.25–7.20 (m, 6H), 7.15–7.08 (m, 4H); ^{13}C NMR (126 MHz, $CDCl_3$): $\delta = 154.51$, 152.12, 130.59, 129.62, 128.71, 128.65, 126.37, 125.06, 123.14, 120.84, 111.36, 107.82.

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