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Unraveling a Biomass-Derived Multiphase Catalyst for the Dehydrogenative Coupling of Silanes with Alcohols under Aerobic Conditions

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38 **KEYWORDS:** Chitosan, Silanes, Alcohols, Dehydrogenative coupling, Silyl ethers,
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41 Oxygen activation, *in-situ* Raman spectroscopy
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46 **ABSTRACT:** Herein, a novel silver and chromium nanostructured N-doped carbonaceous
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49 material has been synthesized by a biomass-annealing approach using readily available
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53 chitosan as a raw material. The resulting catalyst AgCr@CN-800 has been applied for
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3 the dehydrogenative coupling reaction of various silanes with different alcohols to obtain
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7 the corresponding silyl ethers under aerobic and mild conditions. Besides excellent
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10 activity and selectivity, the as-prepared catalyst exhibits good stability and reusability.
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13 Characterization by XRD, XPS, ICP-MS, HRTEM, in combination with careful
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16 examination of the structure with Cs-corrected HAADF-STEM revealed that catalyst
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20 AgCr@CN-800 comprises Ag and CrN aggregated particles, as well as highly dispersed
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23 Ag-N_x and Cr-N_x sites embedded in N-doped graphitic structures. A comparative catalytic
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26 study using structure-related catalysts in combination with acid-leaching treatments has shown
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31 that the most active species are the Ag particles, and that their activity is boosted by the
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34 presence of Cr-derived species. By *in-situ* Raman spectroscopy experiments, it has been
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38 found that the dehydrogenative coupling of silanes with alcohols in the presence of
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41 catalyst AgCr@CN-800 takes place through an oxygen-assisted mechanism.
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51 INTRODUCTION

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4 Silyl ethers are valuable raw materials for the silicon industry as well as important
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7 commodity reagents and protecting groups for alcohols in organic synthesis on laboratory
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10 scale.¹⁻⁵ In addition, these compounds have also attracted the attention of scientists from
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13 the perspective of material science because of their use as reagents for surface coating
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16 and modification,⁶⁻¹³ as well as for the preparation of hybrid organic–inorganic
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19 materials.¹⁴⁻¹⁶
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24 Traditionally, silyl ethers have been synthesized by reaction of halosilanes with alcohols
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27 in the presence of a base, thus resulting in the formation of stoichiometric amounts of
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30 undesired halide salts.¹⁷⁻²⁰ In this context, the catalytic dehydrogenative coupling of
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33 hydrosilanes with alcohols represents a more atom-economical, and hence, a more
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36 environmental-friendly synthetic route.²¹⁻²² Advantageously, since hydrogen is the only
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39 generated by-product, this reaction is also relevant for H₂-generation. In fact, the system
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42 based on alcohol/silane pairs has been considered as a potential liquid organic hydrogen
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45 carrier (LOHCs) that releases H₂ at low temperatures.²³⁻²⁴ However, although this
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48 coupling reaction is thermodynamically favored, the presence of a catalyst is required to
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51 improve the reaction kinetics under mild conditions.
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4 To date, a wide variety of transition-metal-based complexes,²⁵⁻³⁶ alkaline earth
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7 metals,³⁷ and alkali metal bases³⁸⁻³⁹ have been reported as catalysts for the
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10 dehydrogenative coupling of hydrosilanes with alcohols. Moreover, metal-free boron-
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13 based Lewis acids⁴⁰⁻⁴³ and N-heterocyclic carbenes⁴⁴ have also efficiently catalyzed this
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16 reaction. Nevertheless, despite good activity and selectivity toward the production of silyl
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19 ethers achieved by these catalysts, the use of reusable heterogeneous systems is more
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22 advantageous from an environmental point of view.
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28 In recent times, with the aim of dealing with global challenges related to sustainability,
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31 the scientific community has paid much attention toward the use of metal nanoparticles
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34 (NPs) modified by N-doped carbon as catalysts for innovative organic synthesis because
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37 of their good activity and controllable selectivity.⁴⁵ Different strategies have been
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40 developed for the preparation of this kind of nanostructured materials.⁴⁶ Among them, the
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43 *in-situ* formation of both metal NPs and the N-doped graphitic material is a well-
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46 established methodology. Here, non-volatile molecularly defined metal-amine ligated
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49 complexes impregnated on different supports,⁴⁷⁻⁸¹ metal-organic frameworks (MOFs),⁸²⁻
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4 ⁹² or coordination polymers⁹³⁻⁹⁵ are typically used as self-sacrificial templates to obtain
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7 metal NPs embedded in a carbonaceous matrix after pyrolysis under an inert gas.
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10 Alternatively, in order to avoid the use of sophisticated organic ligands and synthetically
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14 demanding routes of sacrificial template materials, pyrolysis of renewable and available
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17 biomass in combination with metal salts represents a more practical catalyst preparation
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20 approach.⁹⁶⁻¹⁰⁵ In this respect, the natural biopolymer chitosan, which is obtained from
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24 industrial fishery bio-waste by deacetylation of shrimp or crab shell-derived chitin, is
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27 especially useful.¹⁰⁶ Chitosan has been proposed as an attractive precursor for obtaining
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31 N-doped carbon materials.¹⁰⁷⁻¹²² In addition, its particular structure containing amino- and
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35 hydroxyl-coordinating groups has made possible its application as a chelating agent for
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38 transition-metals.¹²³⁻¹²⁸
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42 Taking advantage of these properties of chitosan, Garcia and co-workers synthesized
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45 Cu NPs supported on N-doped graphene by firstly preparing a homogeneous solution of
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48 a Cu salt and chitosan, followed by pyrolysis and sonication.¹²⁹ Later, the same group
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51 developed a series of facet-oriented Cu₂O,¹³⁰⁻¹³² Au,¹³³ Pt,¹³⁴ and Ag¹³⁵ NPs on (N-doped)
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56 graphene films prepared by pyrolysis of nanometer-thick films of chitosan embedding the
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4 corresponding transition-metal salt and deposited on a quartz substrate. Importantly, a
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7 variation or even a completely removal of the N content was reported depending on the
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10 pyrolysis temperature and the metal nature. Meanwhile, Beller and co-workers prepared
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13 Co-based N-doped carbon heterogeneous catalysts by using an adapted synthetic
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16 methodology, in which chitosan acts as a solid adsorbent for transition metals instead of
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19 being used in solution before pyrolysis.¹³⁶⁻¹³⁹ In addition to these seminal works, other
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22 catalytic materials synthesized following a similar preparation approach have also been
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27 reported.¹⁴⁰⁻¹⁴⁹

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32 In general, metal-based materials prepared by pyrolysis tend to be heterogeneous in
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35 composition and particle size. In fact, the resulting materials are typically constituted by
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38 metal species of different nature, such as metallic and/or metal oxide NPs. Moreover, the
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41 formation of isolated single-atom sites (ISAS) is also feasible when using supports or self-
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44 sacrificial templates that have a strong coordination ability with metal atoms.¹⁵⁰⁻¹⁵⁸
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48 Concretely, this is the case of chitosan, in which its unique structure containing amino-
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51 and hydroxyl-coordinating groups can promote the formation of ISAS embedded in the N-
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56 doped carbon matrix besides other multiple metal species formed by agglomeration
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3 during uncontrolled pyrolysis.¹⁵⁹⁻¹⁶⁰ This heterogeneity in chitosan-derived N-doped
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7 carbon-based materials makes challenging the identification of active species when they
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10 are used in catalysis, however, it is an essential task for future development of catalysts
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14 with enhanced efficiency.
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17 With regard to the use of heterogeneous catalysts for the dehydrogenative coupling
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20 reaction of hydrosilanes with alcohols, among various available heterogeneous
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23 systems,^{36, 161-179} metal catalysts modified by (doped) graphitic carbon have shown
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27 promising results. Cu NPs supported on doped (-boron and/or -nitrogen) graphene,¹²⁹
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31 $\text{Cu}_2\text{O}^{130}$ or Ag^{135} facet-oriented nanoplatelets on graphene films, as well as, atomically
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34 dispersed Co species anchored on ultrathin two-dimensional N-doped carbon¹⁸⁰ have
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38 been proved to be active catalysts for the title reaction. In addition, the use of a metal-
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42 free hierarchically porous N and S co-doped carbon is also noteworthy.¹⁸¹ Despite these
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45 findings, the relatively high temperature, long reaction times, the need to perform the
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49 reaction under inert atmosphere, and/or the difficulty of preparing catalysts with higher
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52 metal loading offer room for improvement.
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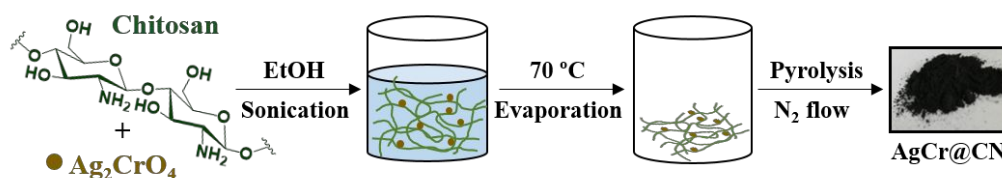
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3 In this contribution, we report the preparation of a N-doped carbonaceous
4 heterobimetallic nanostructured material by pyrolysis of silver chromate (Ag_2CrO_4) highly
5 dispersed on the readily available bio-waste polymer chitosan. We show that the resulting
6 material, which comprises a heterogeneous composition of metal species, efficiently
7 catalyzes the dehydrogenative coupling of hydrosilanes with alcohols under aerobic and
8 mild conditions (even at 0 °C) with excellent selectivity toward the formation of silyl ethers
9 and molecular hydrogen. On the bases of a comparative catalytic study, we demonstrate
10 that catalytic activity mainly arises from the Ag particles and that their activity is boosted by
11 the presence of Cr-derived species. Furthermore, *in-situ* Raman spectroscopic studies have allowed
12 the explanation of the enhanced catalytic activity, which is directly related with the oxygen
13 activation ability of the catalyst.

39 RESULTS AND DISCUSSION

43 Preparation and catalytic performance of catalysts AgCr@CN

44 We started our study by preparing a series of silver and chromium bimetallic catalysts
45 according to the procedure depicted in Scheme 1. A mixture of chitosan and Ag_2CrO_4
46 was homogeneously dispersed in ethanol by sonication. After solvent evaporation under
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3 atmospheric pressure and continuous stirring conditions, the resultant powder was
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7 pyrolyzed at different temperatures in the range from 400 to 900 °C under a nitrogen flow
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10 to yield the heterobimetallic materials AgCr@CN-X, where X stands for the pyrolysis
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13 temperature (see the Experimental Section for more preparation details). The metal
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15 content in the as-prepared materials was determined by inductively coupled plasma mass
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18 content in the as-prepared materials was determined by inductively coupled plasma mass
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21 spectrometry (ICP-MS) analysis. The obtained results revealed an increase of the metal
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24 amount (Ag + Cr) from 13.7 to 18.0 wt% with the pyrolysis temperature because of
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27 increasing weight loss in chitosan decomposition (Table S1). Interestingly, the Ag/Cr ratio
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30 is maintained constant independently of the pyrolysis temperature.
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44 **Scheme 1.** Synthesis of heterobimetallic materials AgCr@CN-X (X = 400-900 °C) used as
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46 catalysts.
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50 With these materials in hand, we evaluated their catalytic performance for the dehydrogenative
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52 coupling of hydrosilanes with alcohols using as a benchmark system the reaction between
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54 dimethyl(phenyl)silane (**1a**) and methanol (**2a**) at 60 °C under aerobic conditions. As shown in
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3 Figure 1a, all prepared heterobimetallic materials displayed catalytic activity with excellent
4 selectivity toward the formation of methoxydimethyl(phenyl)silane (**3aa**) (see also Figure S1). A
5 control experiment revealed that no reaction took place in the presence of a metal-free catalyst (M-
6 free@CN-800) prepared by pyrolysis of chitosan at 800 °C in the absence of Ag₂CrO₄, thus
7 indicating that the catalytically active species are metal-based. The most active catalyst,
8 determined by comparison of the initial reaction rates normalized to the mass of metal weights
9 (Figure 1b), resulted to be the heterobimetallic material pyrolyzed at 800 °C (AgCr@CN-800).
10 Other heterobimetallic catalysts containing silver and a second transition metal different to
11 chromium (W or V), which were also prepared following the same preparation methodology
12 shown in Scheme 1, displayed lower activity for the investigated reaction (Figure S2).
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26 In the presence of the most active catalyst AgCr@CN-800 (15 mg; 2.75 mol% of metal with
27 respect to **1a**), full conversion of **1a** was achieved in 20 min, affording **3aa** in 97 % yield with only
28 residual amounts (< 3 %) and traces (< 1 %) of the corresponding silanol (**4a**) and disiloxane (**5a**)
29 compounds as by-products, respectively (Figure 1c). Moreover, H₂ release was also detected
30 during the reaction between **1a** and **2a**. This dehydrogenative coupling reaction also proceeds well
31 when using lower amounts of catalyst AgCr@CN-800 (5 mg; 0.91 mol% of metal with respect to
32 **1a**), corresponding to a turnover number (TON) of 111. Interestingly, the reaction could also be
33 conducted at lower temperature, 30 °C and even 0 °C, achieving full conversion of **1a** with
34 excellent selectivity to **3aa** in 1 and 2 h, respectively (Figure S3), together with the formation of
35 equimolecular amounts of H₂ (see the Supporting Information). It is worth mentioning that
36 compared to previously reported Ag-based heterogeneous systems, the catalyst AgCr@CN-800
37 catalyzes this reaction at significant lower temperatures (0 °C).^{135, 172, 182-185}
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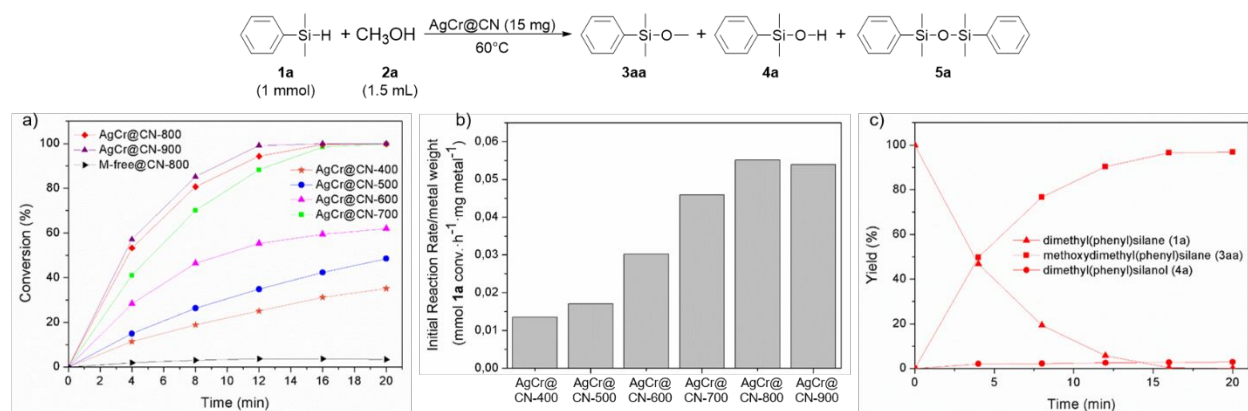


Figure 1. (a) Catalytic performances of catalysts AgCr@CN-*X* (*X* = 400-900) and M-free@CN-800 for the dehydrogenative coupling reaction of **1a** with methanol. (b) Comparison of the metal mass activity. (c) Concentration/time diagram for catalyst AgCr@CN-800.

Interestingly, the reaction rate was significantly increased when pure O₂ was bubbled into the reaction solution providing a 98 % yield of **3aa** within 20 min at 30 °C (TOF = 327 h⁻¹). In contrast, almost no reaction took place when the reaction was carried out under Ar atmosphere, thus revealing that the presence of the catalyst AgCr@CN-800 in combination with O₂ is essential to achieve the dehydrogenative coupling reaction of **1a** with methanol (Figure S3).

Characterization of catalyst AgCr@CN-800

The best heterobimetallic material AgCr@CN-800 in terms of catalytic activity was characterized in detail. The XRD pattern (Figure 2) is dominated by the presence of diffraction peaks associated with the face-centered cubic (*fcc*) structure of Ag⁰ in agreement with the JCPDS database (PDF Card 1-1164). Since these peaks are very sharp, it is expected that this phase is present in the form of large particles. Moreover, a broad shoulder peak in the range of 20–30° (2θ) associated with reflections of the (002) of graphitic carbon could also be inferred.¹⁸⁶ However, no additional peaks corresponding to chromium species were detected.

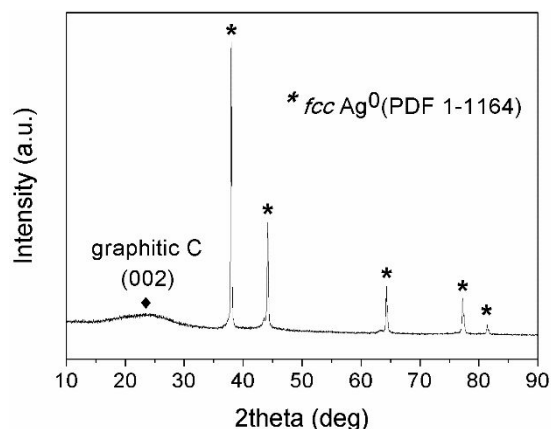


Figure 2. XRD pattern for catalyst AgCr@CN-800.

Transmission electron microscopy (TEM) images show aggregates of metal particles with non-homogeneous sizes of tens to hundreds of nanometers. This broad size distribution is likely generated by partial metal agglomeration during the pyrolysis treatment because of the high metal content (Figures 3a and Figure S4). The high-resolution TEM (HRTEM) images show two types of metal particles of different nature, both coated by few layers of a (defect/N-doped) graphitic carbon shell (Figure 3b-c). The well-resolved lattice spacing of 0.237 nm consistent with the (111) plane of the cubic Ag phase was clearly identified in some of these particles. Besides, an additional phase of chromium nitride (CrN) that displays the characteristic lattice spacing of 0.239 nm associated with its (111) plane was also detected in the HRTEM images. Moreover, the nature of these particles was undoubtedly confirmed by a fast Fourier transform (FFT) analysis, which revealed other characteristic lattice fringe spaces of 0.211 and 0.128 nm associated with the (200) and (311) planes of CrN, respectively (Figure 3c, inset).

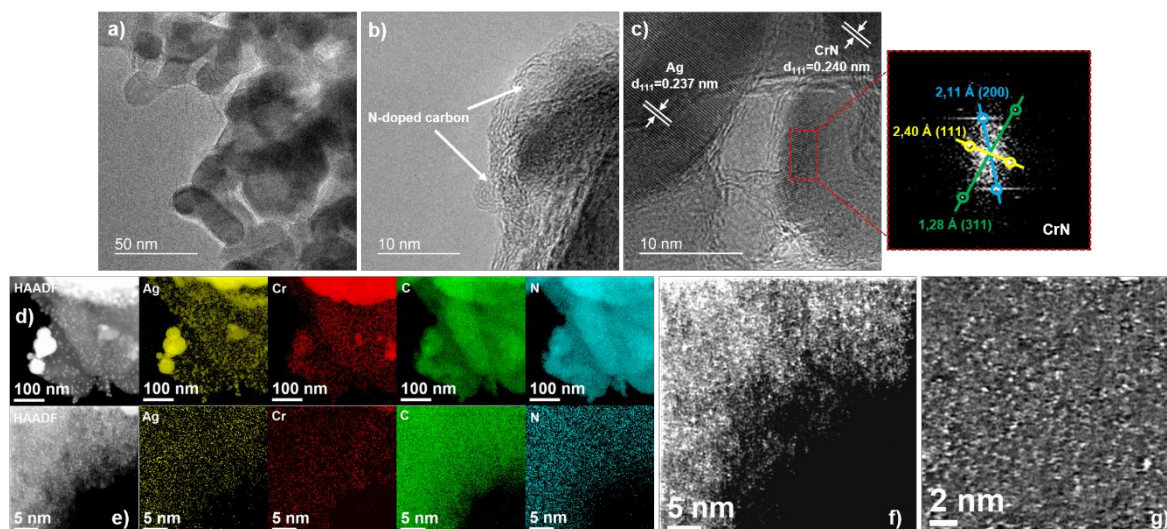


Figure 3. Electron microscopy characterization of catalyst AgCr@CN-800. TEM (a) and HRTEM (b-c) micrographs. The inset shows the FFT from the square region in image c). (d-e) HAADF-STEM images and EDS elemental mapping of Ag, Cr, C, and N. (f-g) High-magnification images for the Cs-corrected HAADF-STEM analysis.

Spherical aberration (Cs)-corrected scanning transmission electron microscopy (STEM) using a high-angle annular dark-field (HAADF) detector coupled with spectroscopic analysis by means of energy dispersive X-ray spectroscopy (EDS) was employed to investigate the structure of catalyst AgCr@CN-800 in a further extent. These studies revealed that Ag, Cr, N, and C elements overlap in spatial locations on each other around the entire sample, including particles (Figure 3d and Figure S5) as well as sites where no particles were visualized (Figure 3e and Figure S5), thus suggesting that metal species may be atomically distributed along the N-doped graphitic material. Interestingly, a closer look at these regions revealed a high density of monodispersed bright dots, likely associated with highly dispersed metal atoms of both Ag and Cr, according to the EDS elemental mapping analysis results (Figure 3f-g and Figure S6-S7).

1 For further characterization of the catalyst surface, X-ray photoelectron spectroscopy (XPS)
2 measurements were performed. The high-resolution Ag 3d core level spectrum displays two
3 peaks at \square 368 and 374 eV associated with the characteristic spin-orbit splitting of Ag 3d_{5/2} and
4 Ag 3d_{3/2} orbitals, respectively, each of them being possible to be fitted into two separated
5 components denoting the presence of two distinct chemical Ag species (Figure 4a). More
6 specifically, the components at 368.1 and 374.1 eV correspond to Ag⁺ species, whereas the ones
7 at 369.3 and 375.3 eV are related to metallic Ag.¹⁸⁷⁻¹⁹¹ The higher contribution of the component
8 associated with Ag⁺ species suggests that, in spite of the shielding effect of thick N-doped
9 graphitic carbon layers encapsulating the Ag particles, these could be constituted by a
10 metallic core and a partially oxidized surface. In addition, it should be considered that the
11 XPS-detectable Ag⁺ species could also arise from highly dispersed Ag⁺ species inserted in the
12 graphitic sheets coordinated to N atoms, that is, as AgN_x sites. Comparison of the obtained
13 electron binding energy of Ag 3d_{5/2} (368.1 eV) in catalyst AgCr@CN-800 with that one for
14 previously reported molecular-defined complexes that contain Ag-N bonds within a related
15 structure (368.4 eV),¹⁹² revealed a prominent increase of the electron density of the Ag⁺ species
16 in the graphitized structure, in good agreement with previous studies.¹⁵⁰
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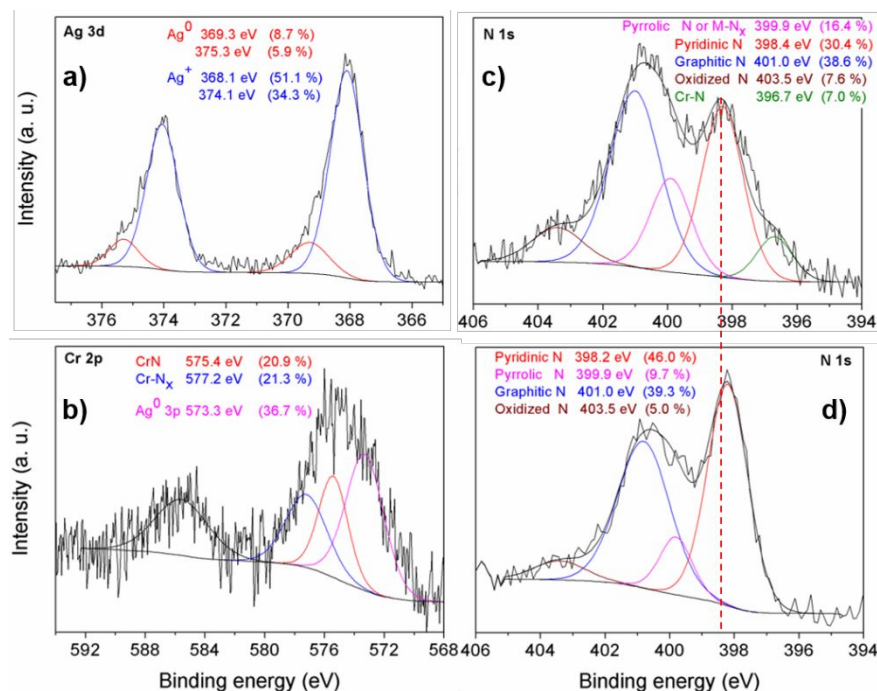


Figure 4. XPS spectra of Ag 3d (a), Cr 2p (b) and N 1s (c) core levels of catalyst AgCr@CN-800. (d) N 1s XPS spectrum of catalyst M-free@CN-800.

Determination of Cr oxidation states in heterobimetallic materials containing Ag is challenging because in the Cr 2p region of the XPS spectrum some Cr species have similar electron binding energy values than that of the Ag 3p peak (573.6 eV) associated with metallic Ag. The Cr 2p XPS spectrum (Figure 4b) for catalyst AgCr@CN-800 shows a broad peak, which could be fitted into three different components after deconvolution. The major peak at 573.3 eV can be ascribed to metallic Ag, whereas, according to the literature, the other two peaks at 575.4 and 577.2 eV denote the presence of CrN¹⁹³ and atomically dispersed Cr-N_x sites embedded in the graphitic sheets,¹⁹⁴ respectively.

The signal deconvolution in the high-resolution N 1s energy-level spectrum (Figure 4c) suggests that catalyst AgCr@CN-800 contains different nitrogen species, at least including pyridinic-N-oxide (403.5 eV), graphitic-N (401.0 eV), pyrrolic-N (399.9 eV) and pyridinic-N (398.4 eV).

1 Furthermore, an additional component (at 396.7 eV) attributed to CrN could also be inferred,
2 which is absent in the XPS spectrum of the metal-free catalyst M-free@CN-800 (Figure
3 4d). Importantly, further comparison of both spectra (Figure 4c and 4d) revealed that while the
4 relative content of graphitic-N and pyridinic N-oxide species is almost the same, an increase of
5 the ratio of pyrrolic-N to pyridinic-N species is observed in catalyst AgCr@CN-800. This
6 increase could be associated with the presence of highly dispersed species attached to pyridinic-
7 N that results in the formation of M-N_x (M = Ag, Cr) sites, whose binding energies fall in the
8 same range as the pyrrolic-N function binding energy. Moreover, an energy shift of over 0.2 eV
9 was detected in the pyridinic-N component of catalyst AgCr@CN-800, thus verifying the
10 existence of metal-N interactions.^{150,152,195}

27 **Acid-leaching and characterization of catalyst AgCr@CN-800-Acid**

29 Catalyst AgCr@CN-800 was leached with acid (see details in the Experimental Section) and
30 further characterized. The Ag and Cr content, determined by ICP-MS analysis, in the leached
31 catalyst (denoted as AgCr@CN-800-Acid) were reduced from 12.74 to 0.12 wt% and from 3.74
32 to 2.29 wt%, respectively. In consequence, no diffraction peaks associated with metallic Ag
33 species were detected in the XRD pattern of the acid-leached catalyst AgCr@CN-800-Acid
34 (Figure 5a). However, besides the broad diffraction peaks of graphitic carbon (at 2θ values of 25.3
35 and 43.6°), other peaks located at 37.5, 43.6, 63.4 and 76.1°, that could be indexed to the (111),
36 (200), (220) and (311) planes, respectively, of the cubic phase of CrN (PDF Card 65-2899),
37 became known in catalyst AgCr@CN-800-acid. This confirms that the acid-leaching treatment
38 fully removed the Ag particles, while keeping almost intact the CrN phase, which is known to
39 display an excellent chemical stability to acids.¹⁹⁶⁻¹⁹⁷

The diffraction peaks associated with CrN are also present in the XRD pattern measured after the acid treatment of a catalyst (AgCr@CN-800-Ar) pyrolyzed under Ar atmosphere instead of using N₂ (see Figure S8). This result, besides the fact that only a slight decrease of the N content (determined by combustion elemental analysis) was detected in catalyst AgCr@CN-800-Ar (7.6 wt %) when comparing with catalyst AgCr@CN-800 (7.8 wt %), proves that the CrN phase is preferentially formed during the pyrolysis treatment by extracting N atoms from chitosan rather than by activation of N₂ gas molecules. Moreover, both catalysts AgCr@CN-800 and AgCr@CN-800-Ar displayed similar catalytic performance for the investigated dehydrogenative coupling reaction between dimethylphenylsilane (**1a**) and methanol (see Figure S8).

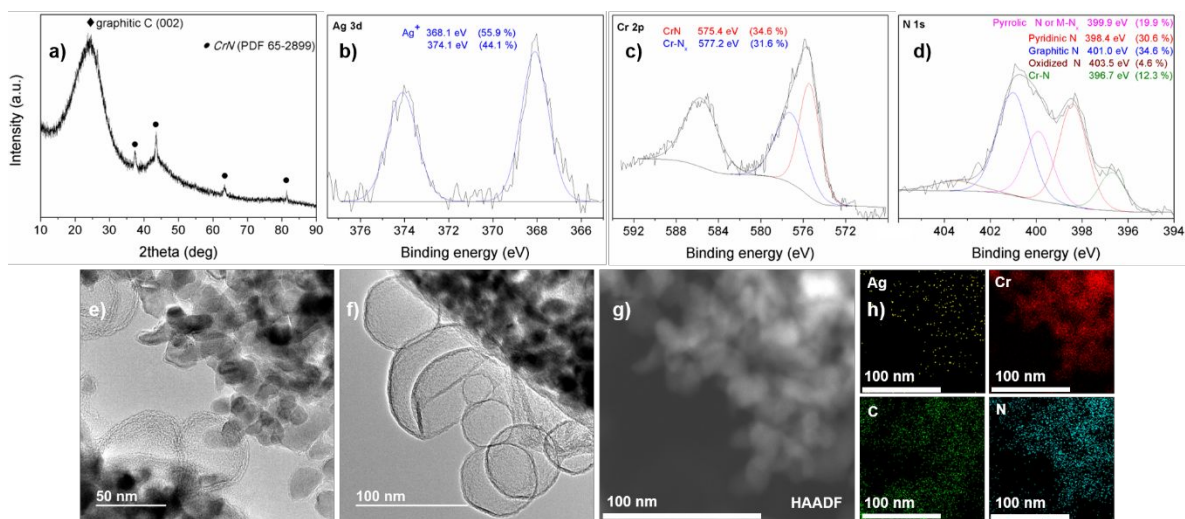


Figure 5. Characterization of catalyst AgCr@CN-800-Acid. (a) XRD spectrum. Ag 3d (b), Cr 2p (c) and N 1s (d) core level XPS spectra. TEM (e, f) and HAADF-STEM (g) images. (h) EDS elemental mapping of Ag, Cr, C, and N.

Morphological characterization of the acid-etched catalyst AgCr@CN-800-Acid by TEM showed the presence of coated nanoparticles (30 nm) as well as hollow-centered (defect/N-doped) graphitic carbon layers (Figure 5e-f). These empty carbonaceous spheres result from the

1 leaching of Ag particles, further confirming the core-shell structure of this
2 heterobimetallic material. The elemental distribution of catalyst AgCr@CN-800-Acid was
3 investigated by EDS elemental mapping (Figure 5g-h), and confirms that, as in the case of
4 catalyst AgCr@CN-800, Cr, C and N elements overlap well in spatial locations, while
5 monodispersed Ag is present in a considerably lower amount, in good agreement with the ICP-
6 MS analysis.
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12 Interestingly, the Ag 3d core level XPS spectrum of catalyst AgCr@CN-800-acid discloses the
13 only presence of Ag⁺ ionic species (i.e. AgN_x sites) represented as two peaks with electron-binding
14 energy values of 368.1 and 374.1 eV after deconvolution and fitting (Figure 5b). It should be noted
15 that the component associated with the Ag 3p peak (573.6 eV) of metallic Ag completely
16 disappeared from the Cr 2p core level XPS spectrum (Figure 5c), being possible to fit the observed
17 peak into two only components corresponding to CrN (575.4 eV) and to atomically dispersed Cr-
18 N_x sites embedded in the graphitic carbon (577.2 eV). On the contrary, no relevant changes are
19 observed in the high-resolution N 1s energy-level spectrum after the acid leaching treatment
20 (Figure 5d).
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33 Based on all characterization results before and after the acid-leaching treatment, we can
34 conclude that catalyst AgCr@CN-800 is a heterobimetallic N-doped carbonaceous material, in
35 which different metal species coexist. More specifically, catalyst AgCr@CN-800 comprises Ag
36 and CrN aggregated particles covered by few layers of defect N-doped graphitic carbon containing
37 highly dispersed Ag-N_x and Cr-N_x species as well.
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46 **Probing into the metal active species**

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48 To unveil which of these species is catalytically active for the investigated dehydrogenative
49 coupling reaction between dimethylphenylsilane (**1a**) and methanol (**2a**) to afford
50 methoxydimethyl(phenyl)silane (**3aa**), the titled reaction was carried out in the presence of
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1 different catalysts (see the Experimental Section and the Supporting Information for preparation
2 and characterization details, respectively). As shown in Figure 6a, a significant decrease of
3 the initial reaction rate (normalized to the mass of metal weights) was achieved by using the
4 acid-etched catalyst AgCr@CN-800-Acid. Nevertheless, it is worth mentioning that reaction
5 proceeded with excellent selectivity after longer reaction times (Figure 6b). Since Ag particles
6 are the species removed with the acid-leaching treatment, this result denotes that they are
7 required for the high activity of catalyst AgCr@CN-800, while the remaining species (i.e.
8 CrN particles and highly dispersed CrN_x and AgN_x sites) contribute in a considerable lower
9 extent to the overall catalytic activity.

10
11 In the presence of a monometallic Ag-based catalyst (Ag@CN-800), which is constituted
12 by core-shell metallic nanoparticles with a narrow size distribution (5-20 nm) and by highly
13 dispersed AgN_x species (see Figure S9 and accompanying discussion), good activity toward the
14 formation of product **3aa** was achieved (Figure 6a) as well. However, in spite of the smaller
15 particle size (and therefore higher specific surface area to interact with the reactants), catalyst
16 Ag@CN-800 is less active than the heterobimetallic one AgCr@CN-800 for the investigated
17 reaction. This result unambiguously corroborates that the presence of chromium-derived
18 species in catalyst AgCr@CN-800 boosts its catalytic activity.

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20 When the monometallic catalyst Ag@CN-800 was leached with acid to remove the metallic
21 Ag nanoparticles, and the resulting material (Ag@CN-800-Acid) only containing highly
22 dispersed Ag-N_x sites (see Figure S10 and accompanying discussion) was used as a catalyst
23 under otherwise the same conditions, a decrease of the selectivity toward the coupling product
24 **3aa** was observed as the conversion increases (Figure 6c). Similarly, the use of catalyst
25 Cr@CN-800-Acid, which is constituted by the same Cr species (i.e. CrN and highly
26 dispersed Cr-N_x sites) than catalyst

AgCr@CN-800-Acid but in the absence of Ag-N_x species (see Figure S11 and accompanying discussion), led to the same loss of selectivity as well (Figure 6d).

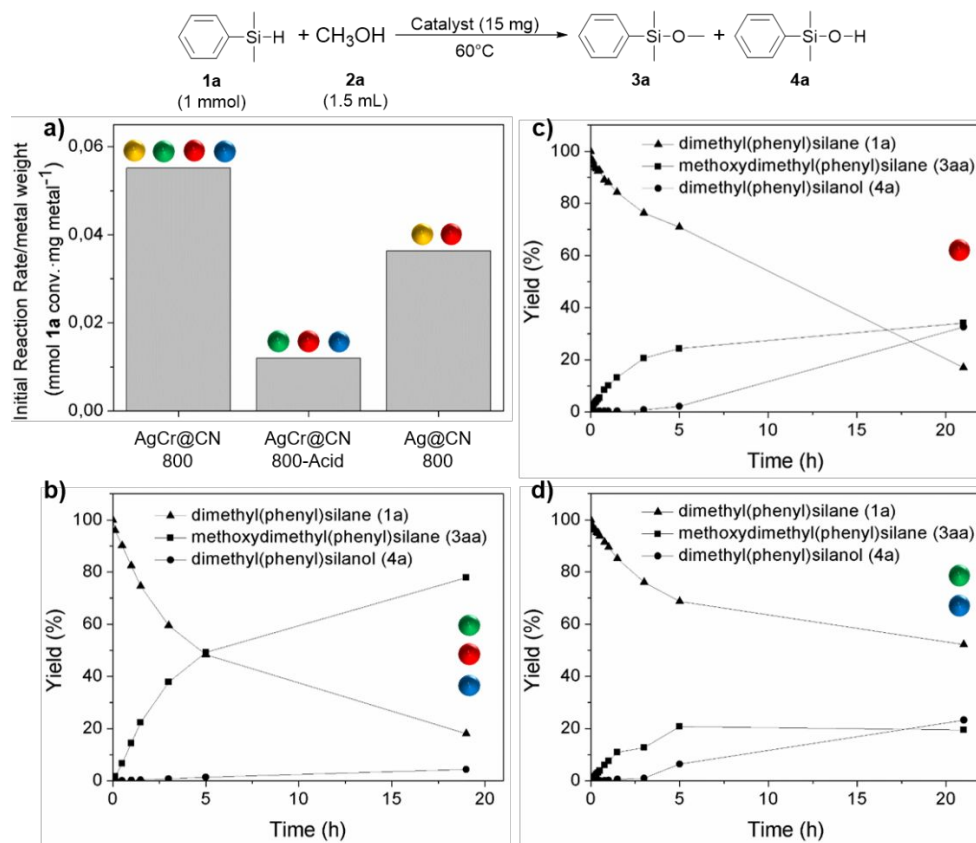


Figure 6. (a) Comparison of the metal mass activity for catalysts AgCr@CN-800, AgCr@CN-800-Acid and Ag@CN-800 in the dehydrogenative coupling reaction of **1a** with methanol (**2a**). Concentration/time diagram for catalyst AgCr@CN-800-Acid (b), Ag@CN-800-Acid (c), and Cr@CN-800-Acid (d). Reaction conditions: **1a** (1 mmol), **2a** (1.5 mL), catalyst (15 mg), 60 °C. Colored dots represent which active species are present in the catalyst used: Ag particles (yellow), CrN particles (green), AgN_x sites (red), and CrN_x sites (blue).

Overall, the above comparative catalytic study reveals that Ag particles are the most active species and that their activity is boosted by the presence of Cr-derived species. In the absence of Ag

1 particles, the rest of metal species (i.e. CrN particles as well as highly dispersed Ag-N_x and Cr-
2 N_x sites) cooperatively catalyze this reaction with a slower reaction rate but with high
3 selectivity. However, a considerably loss of selectivity is achieved when the catalyst only
4 comprises either Ag-N_x sites or Cr-derived species (i.e. CrN particles and Cr-N_x sites),
5 further supporting the synergistic role of Ag- and Cr-derived species in catalyst AgCr@CN-800.
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10 11 **Kinetic and *in-situ* Raman spectroscopy investigations**

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14 To get insights into the reaction pathway for the dehydrogenative coupling of silanes
15 with alcohols in the presence of catalyst AgCr@CN-800, kinetic experiments at 30 °C
16 under air conditions were performed by measuring initial reaction rates at variable
17 concentrations of
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24 the silane **1a** or methanol (**2a**) while keeping constant the other reactant. The initial
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29 reaction rate for the generation of **3aa** was proportional to the concentration of methanol,
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32 but a decrease was observed when increasing the amount of the silane (Figure S12).
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36 According to Hougen–Watson/Langmuir–Hinshelwood principles, developed for
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39 describing reaction mechanisms occurring on the surface of heterogeneous catalysts,
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42 these observations suggest that the alcohol activation is the rate-determining step, and
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45 that both reactants, i.e. the silane and the alcohol, compete by the same active sites.¹⁹⁸⁻
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50 ²⁰¹ Furthermore, a kinetic isotope effect ($k_H/k_D = 2.45$) was observed when using O-
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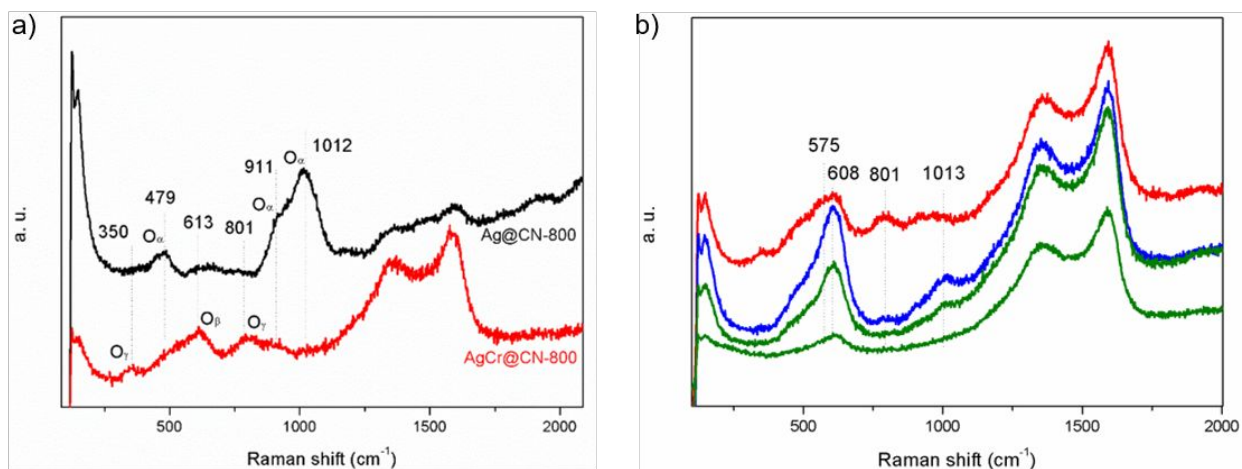
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3 deuterated methanol (CH_3OD) as reactant, further confirming that the activation of the O-
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7 H bond is involved in the slowest reaction step.
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10 As commented above, the presence of O_2 is crucial to accomplish the dehydrogenative
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14 coupling reaction and higher catalytic activity was obtained in the presence of catalyst
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17 AgCr@CN-800 in comparison with the Cr-free catalyst (Ag@CN-800). Thus, with the aim
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20 of getting more clues into the reaction mechanism, we first performed Raman studies of
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24 oxygen activation, revealing that catalyst AgCr@CN-800 displays a higher ability to
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27 activate oxygen than catalyst Ag@CN-800 (Figure 7a). Apart from the G- (1570 cm^{-1}), D-
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30 (1350 cm^{-1}) and 2D- ($2500\text{-}2800\text{ cm}^{-1}$) bands (Figure S13), characteristic of the formation of
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33 graphitic carbon with some degree of defect sites, the recorded spectra for both catalysts display
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36 different Raman bands as consequence of a markedly different reactivity toward O_2 activation.
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39 The Raman spectrum of catalyst AgCr@CN-800 exhibits intense bands at 613 cm^{-1}
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41
42 corresponding to subsurface atomic oxygen species (labelled as O_β), and at 801 and 350
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45 cm^{-1} associated with the stretching and bending vibration of chemisorbed surface atomic
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48 oxygen species (denoted as O_γ).²⁰²⁻²⁰⁴ In the opposite, in catalyst Ag@CN-800 weakly
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53 activated molecular O_2 is predominately observed (Raman bands at 911 and 1012 cm^{-1}
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4 $^{1}203, ^{205}$ together with weakly adsorbed atomic oxygen species at 479 cm^{-1} (denoted as
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7 $O\alpha$). According to previous studies on Ag-based catalysts, the different reactivity toward
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10 oxygen activation observed between both catalysts could arise from structural defects
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13 and/or electronic properties modification in the Ag particles likely provoked in catalyst
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16 AgCr@CN-800 by the presence of Cr species, which are in intimate contact with the Ag
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21 particles, as revealed by electron microscopy characterization.
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25 In order to unravel the role of the surface oxygen species on the reaction mechanism,
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28 “*in-situ*” Raman experiments in the presence of catalyst AgCr@CN-800 were undertaken.
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31 After dosing methanol on a pre-oxidized catalyst, new Raman bands associated to
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34 hydroxyl (575 cm^{-1}) and alkoxy ($\nu(\text{C-O})$ at 1013 cm^{-1}) species emerged concomitant with
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37 the depletion of the bands at 801 cm^{-1} associated with the surface $O\gamma$ species (Figure 7b).
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41 A similar depletion behaviour of these species was also observed after silane dosing on
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44 the pre-oxidized catalyst in the absence of methanol (Figure S14a), further confirming
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47 that both reactants, i.e. the silane and the alcohol, compete by the same active sites, as
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51 revealed the kinetic study. It should be mentioned that the reactivity observed for the
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55 surface $O\gamma$ species is in line with other studies in the literature where they have been
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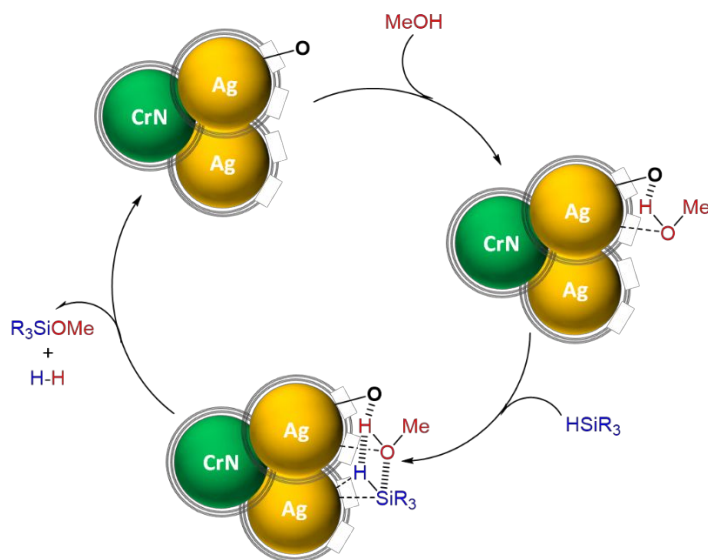
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3 reported as active centres for silane²⁰⁶⁻²⁰⁹ and methanol²⁰⁴ oxidation reactions.
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7 Interestingly, no O-H bond activation of methanol was observed in a non-oxidized catalyst
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10 surface (Figure S14b). This result agrees not only with the fact that no reaction took place
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13 under an inert atmosphere, but also with the higher reaction rate observed by bubbling
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16 pure O₂ gas into the reaction, which agrees with the kinetic findings where methanol
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19 activation was found to be the rate-limiting step.
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42 **Figure 7.** (a) Evolution of the bands in the Raman spectra on catalysts AgCr@CN-800 (red line)
43 and Ag@CN-800 (black line) in a 20% O₂/Ar flow at room temperature. (b) Evolution of the bands
44 in the Raman spectra on catalyst AgCr@CN-800 after sequentially dosing at room temperature a
45 20% O₂/Ar flow (red line), a methanol/Ar flow (blue line), and a silane **1a**/Ar flow (green lines).
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4 Next, the reactivity of the pre-formed methoxy (-OCH₃) and hydroxyl (-OH) species was
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6 investigated after silane feeding. As shown in Figure 7b, the methoxy species (1012 cm⁻¹)
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8 rapidly disappeared in the presence of the silane together with a decrease in the
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10 intensity of the band associated to hydroxyl and subsurface oxygen species (575-613 cm⁻¹)
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1) rapidly disappeared in the presence of the silane together with a decrease in the intensity of the band associated to hydroxyl and subsurface oxygen species (575-613 cm⁻¹), thus indicating that reaction between activated methanol and the silane to form the silyl ether **3aa** and H₂ was accomplished. The fact that the silanol (**4a**) and disiloxane (**5a**) compounds were detected as by-products in the macro-kinetic studies agrees with the herein observed progressive depletion of the Raman bands at 613 and 801 cm⁻¹ associated with subsurface O_β and surface O_γ species, respectively, by further reaction of these species with the silane.



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3 **Scheme 2.** Proposed mechanism for the oxygen-assisted dehydrogenative coupling reaction of
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6 silanes with alcohols in the presence of catalyst AgCr@CN-800.
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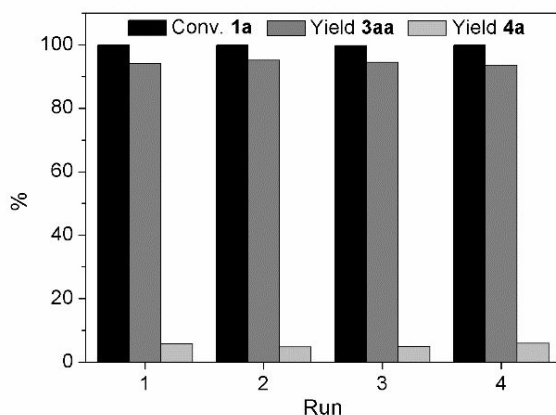
10 Based on these results, a plausible mechanism for the dehydrogenative coupling of
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13 silanes with alcohols in the presence of catalyst AgCr@CN-800 is proposed (Scheme 2).
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17 Oxygen activated Ag surface species act as Brønsted base sites producing hydroxyl and
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20 alkoxy species by reaction with the alcohol. No direct evidence on the silane activation
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23 on the catalyst surface were obtained likely because of it is a fast step of the overall
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26 catalytic reaction. However, considering the well-established reactivity of silanes with
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29 metals, the activation could take place through the formation of a silyl-metal hydride
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32 intermediate by Si-H bond insertion into the Ag surface.²⁰⁶ Subsequently, the nucleophilic
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35 attack of the alkoxy species derived from the alcohol to the electrophilic Si atom of the
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38 silyl-metal hydride intermediate would generate the corresponding silyl ether and
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42 molecular H₂ as well as the recovering of the oxygen activated Ag surface species. It
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48 should be noted that, accordingly to the work of Belkova, Shubina and co-workers,²¹⁰ the
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52 silane activation could also be accounted by coordination of the previously formed
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56 alkoxide ionic species yielding hypervalent pentacoordinate silicon complexes,²¹¹⁻²¹³
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4 which enable the formation of dihydrogen bonded (MeO)₃SiH...HOME species making
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7 straightforward the proton-hydride transfer and H₂ formation.
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11 Reusability of catalyst AgCr@CN-800

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14 In order to investigate the recyclability of catalyst AgCr@CN-800, the model reaction between
15 the silane **1a** and methanol was scaled-up by the factor of seven for practical reasons. After each
16 catalytic run, the catalyst was separated from the reaction mixture, washed with ethyl acetate and
17 diethyl ether, and reused without any reactivation treatment. ICP-MS analysis of the reaction
18 filtrate after each run revealed that the metal (Ag and Cr) content was below the detection limit,
19 thus confirming that no significant metal leaching occurred. Moreover, when the catalyst was
20 removed from the reaction mixture by filtration at 51 % yield of **3aa** the reaction did not proceed
21 any further (Figure S15).
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48 **Figure 8.** Recycling of catalyst AgCr@CN-800 for the dehydrogenative coupling reaction of **1a**
49 with methanol. Reaction conditions: **1a** (7 mmol), **2a** (10.5 mL), catalyst AgCr@CN-800 (105
50 mg), 30 °C, 75 min (run 1), 90 min (run 2) 135 min (run 3) or 180 min (run 4). Conversions and
51 yields determined by GC using anisole as an internal standard (380 μL, 3.5 mmol).
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3 After the fourth run, the morphology of the catalyst was investigated by TEM and EDS elemental
4 mapping (Figure S16). Metal particles were still covered by a few layers of N-doped graphitic
5 carbon shell and good dispersion of all elements (C, N, Ag and Cr) overlapping to each other in
6 spatial locations could also be observed. Furthermore, no significant changes were detected by
7 XRD and XPS analysis (Figure S17). The stability of catalyst AgCr@CN-800, suggested by the
8 characterization results, was further confirmed by the excellent yields of the silyl product **3aa**
9 obtained after each catalytic run with only a slight decrease of the reaction rate, which could be
10 overcome by prolonging the reaction time (Figure 8).
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25 **Reaction scope of catalyst AgCr@CN-800**

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28 The catalytic performance of catalyst AgCr@CN-800 was further explored for the
29 dehydrogenative coupling of various silanes with different alcohols. As shown in Table 1,
30
31 excellent selectivity to the corresponding alkoxysilane products (**3ab-ag**) was achieved in
32 the reaction between dimethylphenylsilane (**1a**) and alcohols (**2b-g**) with longer alkyl
33
34 chain length, including linear and branched ones. (Table 1, entries 1-7). Comparing to
35 methanol, longer reaction times were needed for full (or high) conversions, most likely
36 because of steric effects. Benzyl alcohol (**2h**) also reacted efficiently at higher
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38 temperature (100 °C) with silane **1a** affording the desired silyl ether product (**3ah**) in 91
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4 % selectivity (Table 1, entry 8). Interestingly, when the reaction was performed in the
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7 presence of ethylene glycol, the silyloxy(ethan-1-ol) product (**3ai**) was afforded with high
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10 selectivity (Table 1, entry 9). Besides silane **1a**, triphenyl- (**1b**), diphenyl- (**1c**), and
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13 phenylsilane (**1d**) were also excellent candidates to accomplish the dehydrogenative
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15
16 coupling reaction with different alcohols in the presence of catalyst AgCr@CN-800 to the
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19 corresponding mono- (**3ba**), di- (**3ca**, **3cc**, **3cd**), and trialkoxysilane (**3da**) products with
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22 good to excellent selectivity (Table 1, entries 10-14). In general, the discrete loss of
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25 selectivity is associated with the formation of the corresponding silanol, disiloxane and/or
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28 siloxane oligomer products by reaction of silanes with oxygen activated Ag surface
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31 species and/or with ubiquitous water present in alcohols.
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39 **Table 1** Dehydrogenative coupling of silanes and alcohols catalyzed by AgCr@CN-800^a

Entry	Silane	Alcohol	Time [min]	Conversion ^b [%]	Selectivity to 3b [%]
1 ^c	Me ₂ PhSiH (1a)	MeOH (2a)	20	>99	97 (89) ^d
2	Me ₂ PhSiH (1a)	EtOH (2b)	60	>99	93
3 ^c	Me ₂ PhSiH (1a)	<i>n</i> -PrOH (2c)	60	>99	94
4 ^e	Me ₂ PhSiH (1a)	<i>n</i> -BuOH (2d)	180	96	96
5 ^{c, e}	Me ₂ PhSiH (1a)	<i>n</i> -HexOH (2e)	60	97	96
6 ^e	Me ₂ PhSiH (1a)	<i>i</i> -PrOH (2f)	60	99	85
7	Me ₂ PhSiH (1a)	<i>sec</i> -BuOH (2g)	360	99	89
8 ^{e, f}	Me ₂ PhSiH (1a)	BzOH (2h)	120	95	95
9	Me ₂ PhSiH (1a)	HOEtOH (2i)	60	>99	(79)

10 ^c	Ph ₃ SiH (1b)	MeOH (2a)	60	95	(93)
11 ^c	Ph ₂ SiH ₂ (1c)	MeOH (2a)	45	99	89
12	Ph ₂ SiH ₂ (1c)	<i>n</i> -PrOH (2c)	45	99	(92)
13	Ph ₂ SiH ₂ (1c)	<i>n</i> -BuOH (2d)	60	99	(80)
14 ^{c, g}	PhSiH ₃ (1d)	MeOH (2a)	20	99	89

^aReaction conditions: silane (1 mmol), alcohol (1.5 mL), AgCr@CN-800 (15 mg), 60 °C.

^bDetermined by GC using anisole (54 μL, 0.5 mmol) as an internal standard. Yield of isolated products in parentheses. ^cAnhydrous alcohol as reactant. ^dIsolated yield on a gram-scale reaction: **1a** (1 g), MeOH (11 mL), AgCr@CN-800 (110 mg), 30 °C, 75 min. ^eAgCr@CN-800 (30 mg). ^f100 °C. ^gAgCr@CN-800 (5 mg).

CONCLUSIONS

We have developed a series of N-doped carbonaceous heterobimetallic nanostructured materials prepared by pyrolysis of chitosan at different temperatures in the presence of highly dispersed Ag₂CrO₄. Their catalytic potential has been investigated for the dehydrogenative coupling reaction of various silanes with different alcohols. The most active catalyst AgCr@CN-800 catalyzes this reaction under aerobic and mild conditions, even at 0 °C, affording the corresponding silyl ether products with excellent selectivity. Furthermore, the catalyst displays good stability and recyclability.

Characterization results revealed that catalyst AgCr@CN-800 comprises Ag and CrN aggregated particles, as well as highly dispersed Ag-N_x and Cr-N_x sites embedded in N-doped graphitic structures. The rational design of structure-related catalysts in combination with acid-leaching treatments allowed for carrying out catalytic control experiments, which revealed that the most active species are the Ag particles and that their activity is boosted by the presence of Cr-derived species. It has been demonstrated by *in-situ* Raman spectroscopy that this boosting effect

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3 is related with a higher ability for the generation of oxygen activated surface species, which has
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6 resulted to play a crucial role as Brønsted base sites for the dissociative activation of the alcohol
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9 that is the rate-determining step of the whole process.

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11 This work not only provides solid evidences of a catalyst involving surface oxygen activated
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13 species as key active sites for environmentally benign reactions for green organic synthesis, but
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15 also offers insights for disentangling the heterogeneous composition of chitosan-derived annealed
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17 materials containing metals.
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21 22 **EXPERIMENTAL SECTION**

23 24 25 **Reagents**

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28 Ag_2CrO_4 was synthesized according to the co-precipitation method previously reported in
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31 the literature.²¹⁴ $\alpha\text{-Ag}_2\text{WO}_4$ and $\alpha\text{-AgVO}_3$ were prepared according to literature methods
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35 as well.²¹⁵⁻²¹⁶ Chitosan, silanes and alcohols, including anhydrous methanol, were
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38 obtained from commercial sources (Sigma Aldrich) and were used as received, while *n*-
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41 propanol and *n*-hexanol were dried over molecular sieves prior to be used.
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46 47 **Synthesis of catalysts AgCr@CN**

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49 In a 250 mL beaker, Ag_2CrO_4 (0.074 g) and chitosan (0.926 g) were dispersed by
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52 sonication in 30 mL of ethanol for 20 min. Then, the solvent was evaporated under
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3 atmospheric pressure and stirring conditions at 70 °C, and the residue was dried
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7 overnight at this temperature under high vacuum. The dried sample was transferred into
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10 a quartz tube, and pyrolyzed at temperatures between 400-900 °C for 2 h in a vertical
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13 tubular oven with a ramp rate of 10 °C/min while flushing N₂ through the tube constantly
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17 until the oven was cooled down to room temperature. The resulting material was ground
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20 in an agate mortar and stored in an Eppendorf under air. Catalyst M-free@CN was
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23 prepared by directly pyrolyzing chitosan (1 g) under the same annealing treatment,
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27 followed by grinding in an agate mortar.
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32 **Synthesis of AgW@CN-800 and AgV@CN-800**

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35 The preparation of catalysts AgW@CN-800 and AgV@CN-800 was carried following
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38 the same procedure to the one described for AgCr@CN materials. 0.070 g of α -Ag₂WO₄
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41 or 0.078 g of α -AgVO₃, and 0.930 g or 0.922 g of chitosan, respectively, were used as
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44 precursors. The other experimental procedures were the same, and the pyrolysis
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48 temperature was 800 °C.
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53 **Preparation of catalyst AgCr@CN-800-Acid**

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1 AgCr@CN-800-Acid was prepared by acid leaching of AgCr@CN-800. In a 100 mL beaker,
2 200 mg of catalyst AgCr@CN-800 were dispersed in a 0.5 mol/L H₂SO₄ aqueous solution (50
3 mL) under stirring conditions and heated at 75 °C for 6 h. After that, the resulting material
4 was recovered by centrifugation, washed twice with water, twice with ethanol and dried at
5 60 °C overnight.
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10 11 **Synthesis of Ag@CN-800**

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15 Chitosan (0.924 g) was dispersed by sonication for 20 min in an ethanol solution of AgNO₃
16 (0.076 g in 30 mL). The other experimental procedures were the same the ones described
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18 for AgCr@CN materials, and the pyrolysis temperature was 800 °C.
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34 **Synthesis of Ag@CN-800-Acid**

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37 Ag@CN-800-Acid was prepared by five consecutive acid leaching treatments starting from
38 240 mg of catalyst Ag@CN-800. After each treatment, the resulting material was
39 recovered by centrifugation, washed twice with water, twice with ethanol, dried at 60 °C, and
40 used for the next one. The first three acid leaching treatments were carried out in a 100 mL
41 beaker, in which the catalyst was dispersed in a 1, 2 or 4 mol/L H₂SO₄ aqueous solution (50
42 mL), respectively, under stirring conditions and heated at 75 °C for 16 h. The last two acid
43 leaching treatments were performed in a 100 mL Teflon vessel containing a stirring bar. Once
44 the materials were dispersed
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3 in a 4 mol/L H₂SO₄ aqueous solution (50 mL), the Teflon vessel was sealed and heated at 120 or
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5 140 °C, respectively, under stirring conditions for 2 h with a heating rate of 5 °C/min in a
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7 microwave equipment using an irradiation power of maximum 800 W.
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10 11 **Synthesis of Cr@CN-800-Acid**

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14 Chitosan (0.957 g) was dispersed by sonication for 20 min in an ethanol solution of K₂CrO₄
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16 (0.043 g in 30 mL). Afterward, the solvent was evaporated under atmospheric pressure and stirring
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18 conditions at 70 °C, and the residue was dried overnight at this temperature under a high *vacuum*.
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20 Then, the dried sample was transferred into a quartz tube, and pyrolyzed at 800 °C for 2 h in a
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22 vertical tubular oven with a ramp rate of 10 °C/min while flushing N₂ through the tube constantly
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24 until the oven was cooled down to room temperature again. The resulting material was ground in
25
26 an agate mortar and transferred to a 100 mL beaker containing a stirring bar where it was dispersed
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28 in a 1 mol/L H₂SO₄ aqueous solution (50 mL) under stirring conditions and heated at 75 °C for 16
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30 h. This material was recovered by centrifugation, washed twice with water, twice with ethanol,
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32 and dried at 60 °C.
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39 **Characterizations**

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42 Powder X-ray diffraction (XRD) measurements were performed in a D/MAX-2500 PC
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44 diffractometer (Rigaku) with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$). Samples for electron microscopy
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46 studies were prepared by sprinkling the material directly onto the holey-carbon-coated nickel or
47
48 copper grids. Some of the measurements were performed in a JEM 2100F microscope operating
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50 at 200 kV both in transmission (TEM) and in scanning-transmission modes (STEM). C_s-corrected
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52 Scanning Transmission Electron Microscopy (STEM) measurements were performed in a probe
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3 corrector Titan Themis operated at 300 kV. X-ray photoelectron spectra were acquired with a
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5 monochromatic Al K α X-ray source (1486.6 eV) using a pass energy of 20 eV on a Kratos AXIS
6
7 ultra DLD spectrometer. The C1s peak at 284.6 eV was used to provide a precise energy
8
9 calibration. The metal content in catalysts was determined by inductively coupled plasma mass
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11 spectrometry (ICP-MS) using an ICP-MS Agilent 7500 CX spectrometer. Samples for ICP-MS
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13 analysis were previously digested in a microwave equipment (CEM Corp, Matthews, NC)
14
15 equipped with a temperature controller (MARS6 iWave). A previously weighted amount of
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17 material and 10 mL HNO₃ (65 % p/p) were introduced in a 100 mL Teflon vessel, sealed and
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19 heated at 210 °C under static conditions for 25 min with a heating rate of 12 °C/min by
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21 irradiating at a maximum power of 1800 W. After cooling down to room temperature, the
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23 resulting solution was transferred to a previously tared 25 mL-volumetric flask and diluted with
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25 MiliQ H₂O.
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31 ¹H-NMR spectra of isolated products were recorded on a Bruker AV 300 spectrometer. All
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33 chemical shifts (δ) are reported in parts per million (ppm) and coupling constants (J) in Hz. For
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35 ¹H-NMR and ²⁹Si-NMR chemical shifts are reported relative to tetramethylsilane (δ 0.0 ppm in
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37 CDCl₃) or *d*-solvent peaks (δ 77.16 ppm CDCl₃) for ¹³C-NMR. GC analyses were obtained on a
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39 Shimadzu GC-2010 apparatus equipped with a FID and a Technokroma (TBR-5MS, 30 m x 0.25
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41 mm x 0.25 μ m) column. GC-Mass characterization was carried out on a GC-Mass Agilent 6890
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43 Network equipped with a capillary column Agilent (HP-5, 30 m \times 0.32 mm \times 0.25 μ m) and a mass-
44
45 selective detector. The unambiguously detection of the H₂ evolved from the reaction was carried
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47 out using an Agilent 490 MicroGC equipped with two columns (Pore Plot Q and MolSieve 5A)
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49 and one thermal conductivity detector (TCD).
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54 Raman spectra were recorded at room temperature using a 514 nm laser excitation on a Renishaw
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56 Raman spectrometer (“in via”) equipped with a CCD detector. The laser power on the sample was
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3 10-50 mW and a total of 20 acquisitions (10 s exposure time) were taken for each spectrum.
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5 Analyses on different positions of the sample were recorded (spectral resolution 2 μ m).
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7 Measurements were carried out using a home-made cell, where the catalyst powder was introduced
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9 without any previous treatment.
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13 **General procedure for the catalytic dehydrogenative coupling of silanes and alcohols**

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17 Catalytic experiments were performed under aerobic conditions in a 50 mL round-bottom flask
18
19 equipped with a reflux condenser and a magnetic stirring bar. Once the catalyst (15 mg) and the
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21 alcohol (1.5 mL) were introduced, the reaction flask was heated at 60 °C and let equilibrate for 5
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23 min. Then, the silane (1 mmol) and anisole (54 μ L, 0.5 mmol) as an internal standard were added,
24
25 setting this point as the starting time of the reaction. Yields and conversions were determined by
26
27 GC analysis taking samples from the reaction mixture at the reported times. No internal standard
28
29 was added in reactions from which isolated yields were calculated. After reaction completion and
30
31 dilution with ethyl acetate, the catalyst was separated off by filtration, and the solvent was removed
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33 under reduced pressure. Some of the products were purified by flash-column chromatography
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35 using *n*-hexane as an eluent phase (see the Supporting Information). For the recycling experiments,
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37 the general procedure was scaled up by the factor of 7, and the reaction was performed at 30 °C in
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39 an opened 50 ml centrifugation tube. After reaction completion, the reaction mixture was diluted
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41 with ethyl acetate, and the catalyst was separated off by centrifugation, cleaned with ethyl acetate,
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43 diethyl ether, and dried at 60 °C for 30 min before using for the next run again.
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50 **ASSOCIATED CONTENT**

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4 The Supporting Information is available free of charge via the Internet at
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7 <http://pubs.acs.org>.
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11 Extended data for the characterization of catalysts, additional catalytic and Raman
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13 spectroscopic experiments, and characterization data of isolated products.
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18 19 **Notes** 20

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23 The authors declare no competing financial interest.
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27 **ACKNOWLEDGMENT** 28

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31 The authors thank the financial support from MICIU/AEI/FEDER (PGC2018-094417-B-
32
33 I00 and RTI2018-098237-B-C22) and Universitat Jaume I (UJI-A2019-16, UJI-B2019-30,
34
35 and UJI-B2018-23). I. S. thanks the Spanish Ministerio de Economía, Industria y
36
37 Competitividad (MINECO) for a postdoctoral “Juan de la Cierva-Incorporación” fellowship
38
39 (IJCI-2016-30590), and the financial support from the “José Castillejo” Mobility Program
40
41 (CAS19/00339) of the Ministerio de Ciencia, Innovación y Universidades (MICIU). S. M.
42
43 acknowledges DGA/fondos FEDER (construyendo Europa desde Aragón) for funding the
44
45 research group Platón (E31_17R). D. V-E. thanks the MICIU for a FPU grant
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3 (FPU15/03011). E. L. and M. A. thank the financial support from FAPESP (2013/07296-
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6
7 2), CNPq (166281/2017-4), CAPES, and FINEP. The authors also thank the “Servei
8
9
10 Central d’Instrumentació Científica (SCIC)” of the Universitat Jaume I, as well as Dr. G.
11
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13
14 Antorrena for technical support in XPS studies.
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