An Effective and Reusable Hyperbranched Polymer Immobilized Rhodium-Catalyst for the Hydroformylation of Olefins

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Abstract

The hydroformylation remains the most applied industrial process to produce aldehydes. Much research has been devoted to developing new catalyst systems since aldehydes are highly desired. Supported metal catalyst complexes have drawn renewed attention due to an increased interest in benign and environmental processes. In this paper, NiXantphos has been immobilized on hyperbranched poly(aryleneoxindole) supports, different in linker, via a one-step post-functionalization. Two heterogeneous hyperbranched poly(aryleneoxindole) supported NiXantphos ligands were evaluated in the microwave assisted rhodium catalyzed hydroformylation of olefins. After selecting the best reaction conditions, a variety of functionalized olefins was successfully converted into the desired linear aldehydes working under milder conditions compared to known processes, in terms of syngas pressure (4.8 bar), temperature (75 °C) and reaction times (20 min). The increased activity might emanate from a positive dendritic effect unique to the dendritic nature of the support. Furthermore, the catalyst system was successfully

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3 recovered and reused without a decrease in activity nor regioselectivity, thus
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7 demonstrating to be a valid alternative to classical homogenous procedures.
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10 11 12 **1. Introduction** 13 14 15

16 The oxo process represents one of the most atom economic, straightforward
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19 approaches to the synthesis of aldehydes starting from olefins and syngas in the
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22 presence of a metal catalyst. The transformation discovered by Otto Roelen in 1938¹ is
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25 still nowadays the most applied catalytic process in industry being used for the production
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28 of more than 6 million tons of aldehydes every year.²⁻⁴ Aldehydes are versatile functional
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31 groups widely used as reaction intermediates for the preparation of polymers,
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34 pharmaceuticals, agrochemical, food and fragrance compounds.⁵⁻⁶ As a catalytic process
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37 many efforts has been made on developing new catalysts based on different metals
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40 starting from the classical Co⁷⁻⁸ and Rh,⁹⁻¹⁰ arriving to the more recently investigated Ru,
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43 Pd, Ir, and Fe¹¹ based complexes.¹² One of the main problems in hydroformylation is
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46 represented by the regioselectivity of CO addition to the double bond towards the
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49 selective production of linear aldehydes.¹³⁻¹⁶ For this purpose, in the '90s, bulky bidentate
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diphosphine ligands have been introduced for the regioselective hydroformylation of both internal and terminal olefins.¹⁷⁻¹⁸ The application of this transformation in domino and tandem protocols has been successfully explored¹⁹⁻²⁰ as well as the use of microwaves in dedicated instruments instead of stainless steel autoclaves with traditional heating.²¹⁻

²² Known heterogeneous catalysts for hydroformylation are usually supported on materials such as silica-based,²³ ZnO,²⁴ graphene,²⁵ sol-gel,²⁶ nanoparticles²⁷ on silica,²⁸⁻
²⁹ carbon,³⁰ porous organic polymers (POPs),³¹ linear or cross-linked polymers³² and many others.³³ Nevertheless many of the reported protocols require high temperatures (> 90 °C) and pressure (> 10 bar) for long reaction times (> 24 h). The application of dendrimers in catalysis has attracted the attention of many scientists.³⁴⁻³⁸ This can be explained by an often observed improvement in the catalytic performance (formally expressed per catalytic unit) due to the so called dendritic effect, which can have various origins.³⁹⁻⁴¹ The dendritic effect has also been observed in hydroformylation.^{39, 42-43} Alper *et al.* described a remarkable activity for rhodium complexed to dendrimers on a resin allowing hydroformylation under mild conditions with high selectivity presumably due to a cooperative effect.⁴⁴⁻⁴⁵ Hyperbranched polymers (HBs) are, as far as we know, much less

investigated as catalyst supports despite having similar properties to dendrimers and thus could also benefit from such a dendritic effect.⁴⁶⁻⁴⁷ In contrast to dendrimers, HBs are prepared in a one-step procedure and are easily purified. A recent report by Rossi *et al.* describes an improved catalytic activity when modifying rhodium nanoparticles with hyperbranched polyesters for the hydroformylation of natural products.⁴⁸ The increased activity presumably originates from improved metal support interaction and/or a more active rhodium species on the catalyst surface. Mecking *et al.*⁴⁹ reported the application of HBs with sulfonated triphenylphosphine counter ions in the hydroformylation of 1-hexene. The group of Haag investigated two strategies to covalently attach NiXantphos to HB polyglycerol.⁵⁰ Unfortunately, poor selectivity or conversion was achieved in the hydroformylation of *N*-allyl-phthalimide with the supported complexes. To the best of our knowledge, additional HB supported rhodium complexes are only reported for hydrogenation.⁵¹⁻⁵³ Clearly, HBs as recoverable supports in combination with rhodium are poorly investigated despite their potential and versatility. We previously reported a recoverable hyperbranched poly(aryleneoxindole)s (HBPAOs) sulfonated acid catalyst.⁵⁴⁻

We here report the preparation of a new HBPAO derivatives charged with NiXantphos (Figure 1), a xanthene-based phosphine ligand, able to immobilize Rh. The new HBPAOs have been efficiently applied in the hydroformylation of functionalized terminal olefins and the recycling of the catalytic system as well as the metal leaching have been considered.

Figure 1. Structures of heterogeneous ligand **1a**, **1b** and homogeneous ligand Xantphos.

2. Experimental section

2.1. General information

Unless otherwise stated, all reagents were purchased from commercial suppliers and used without further purification. All microwave reactions are performed in a CEM Discover microwave oven equipped with a 10 mL tube for reactions under pressure and an external IR sensor to detect the reaction temperature during the irradiation. Mass spectra were recorded using a Thermo Electron LCQ Advantage fed by an Agilent 1100 pump and injection system. Data were analyzed using Xcalibur software. ¹H and ¹³C NMR

spectra were recorded on a Bruker Avance 300, 400 or 600 spectrometer at room temperature. Chemical shifts are reported in parts per million (ppm) and are referenced to the internal standard tetramethylsilane. ^{31}P NMR spectra were recorded on a Bruker Avance 600 spectrometer at room temperature. Chemical shifts are reported in ppm and are referenced to the external standard 25 vol% H_3PO_4 (present in a coaxial tube insert). MPLC flash chromatography was performed using a Büchi SepacoreTM flash apparatus. The molecular weights of the polymers were determined by gel permeation chromatography (GPC). Thermogravimetric Analysis (TGA) was carried out using a SDT Q600 instrument. Total-reflection X-ray fluorescence (TXRF) of the samples was measured on a Bruker S2 Picofox TXRF spectrometer. IR spectra were recorded on a Bruker Alpha-T FT-IR spectrometer. The amount of rhodium leached in solution was measured with an Inductive Coupled Plasma Optical Emission Spectrometer ICP-OES 710.

2.2. Synthesis of supported ligands

Br-HBPAO 4a and 4b: A flame-dried nitrogen flushed vial was filled with A_2 monomer **2a** or **2b** and B_3 monomer **3** (equimolar) in $\text{CH}_3\text{SO}_3\text{H}$ ($c = 0.05 \text{ M}$). The reaction mixture

was heated and stirred at 50 °C for 48 hours. The reaction mixture was quenched in distilled H₂O. The precipitate was filtered and washed with distilled H₂O and acetone. The precipitate was dried redissolved in DCM and precipitated in MeOH under vigorous stirring (DCM:MeOH 1:100). Br-HBPAO polymer (**4a** or **4b**) were filtered, washed with MeOH and dried.

Br-HBPAO (**4a**): beige powder; ¹H NMR (300 MHz, CDCl₃) δ = 8.31 (br s, 2H), 7.82 (br s, 5H), 7.40 (br m, 5H), 7.24 – 6.63 (br m, 16H), 3.78 (br s, 2H), 3.39 (br s, 2H), 1.93 (br s, 2H), 1.59 (br m, 2H), 1.04 (br s, 6H); ¹³C NMR (600 MHz, CDCl₃) δ = 193.6, 177.5, 162.4, 155.2, 142.0, 138.5, 133.5, 132.6, 130.7, 130.2, 124.9, 123.2, 120.4, 120.2, 117.6, 117.3, 61.3, 39.0, 30.6, 30.1; GPC (THF) Mn: 3 kDa Mw: 7 kDa PDI: 2.06; IR: ν = 3065, 2954, 1712, 1658, 1584, 1488, 1233, 1160, 1005, 844, 745, 618, 488.

Br-HBPAO (**4b**): beige powder; ¹H NMR (300 MHz, CDCl₃) δ = 8.31 (br s, 2H), 7.89 – 7.72 (br m, 6H), 7.45 – 7.28 (br m, 5H), 7.24 – 6.79 (br m, 18H), 3.94 (br s, 2H), 3.41 (br s, 2H), 2.28 (br s, 2H); ¹³C NMR (600 MHz, CDCl₃) δ = 193.6, 177.1, 162.4, 161.9, 155.2, 154.6, 138.5, 138.5, 133.5, 132.6, 130.2, 130.1, 124.9, 120.4, 120.2, 117.6, 117.3, 108.7, 61.3, 45.4, 38.4, 36.5, 33.9, 28.6, 26.6; GPC (THF) Mn: 5 kDa Mw: 8 kDa PDI: 1.69; GPC

(THF:DMF 1:1 + 0.05M LiBr) Mn: 13 kDa Mw: 30 kDa PDI: 2.27; GPC-MALS (THF) Mn: 10 kDa Mw: 16 kDa PDI: 1.56; IR: ν = 3055, 1713, 1659, 1586, 1491, 1235, 1161, 1109, 1006, 868, 844, 476, 693, 494.

NiX-HBPAO 1a and 1b: A flame dried flask was filled with NaH (3.0 equiv compared to the Bromide load of Br-HBPAO) and NiXantphos (1.1 equiv compared to Br load Br-HBPAO) in DMF (10 mL/g Br-HBPAO, dried on molecular sieves 4Å overnight and degassed for 10 min prior to use) under Argon atmosphere. The mixture was stirred at 100 °C for 1h and changed from a colorless to an orange solution. A solution of Br-HBPAO **4a** or **4b** in DMF (2.5 mL/g Br-HBPAO, dried on molecular sieves 4Å overnight and degassed for 10 min prior to use) was added dropwise at room temperature and the mixture was stirred at 100 °C. The reaction mixture was quenched in distilled H₂O (degassed prior to use) the next day. The precipitate was filtered, washed with distilled H₂O (degassed) and Acetone. The precipitate was further purified, after drying, by dissolving in DCM, precipitating with EtOAc and washing with EtOAc and Acetone to remove the excess of NiXantphos. The precipitate was dried via Schlenk line obtaining NiX-HBPAO **1a** or **1b**. Note: the reaction was very sensitive to water or oxygen.

NiX-HBPAO (**1a**): red-brownish powder; ^1H NMR (400 MHz, CDCl_3) δ = 8.31 (br s, 2H), 7.81 (br s, 5H), 7.23-6.75 (br m, 30H), 6.63 (br s, 2H), 6.44 (br s, 1H), 5.97 (br s, 1H), 3.84 (br s, 2H), 3.59 (br s, 2H), 1.67 (br s, 4H), 1.14 (br s, 6H). ^{31}P NMR (400 MHz, CDCl_3) δ = -18.95; GPC (THF) Mn: 7 kDa Mw: 9 kDa PDI: 1.28 ; IR: ν = 3055, 2953, 1710, 1659, 1587, 1488, 1417, 1357, 1159, 1106, 1007, 856, 738, 690, 495.

NiX-HBPAO (**1b**): dark brown-greenish powder; ^1H NMR (600 MHz, CDCl_3) δ = 8.32 (br s, 2H), 7.81 (br s, 6H), 7.24-6.63 (br m, 38H), 6.52 (br s, 1H), 6.29 (br s, 1H), 5.98 (br s, 1H), 3.94 (br s, 2H), 3.54 (br s, 2H), 2.12 (br s, 2H). ^{31}P NMR (600 MHz, CDCl_3) δ = -18.77; GPC (THF:DMF 1:1 + 0.05M LiBr) Mn: 7 kDa Mw: 17 kDa PDI: 2.46 ; IR: ν = 3052, 1712, 1659, 1585, 1491, 1463, 1414, 1233, 1160, 1002, 843, 741, 691, 492.

2.3. Hydroformylation reaction

NiX-HBPAO **1b** was added to a solution of $\text{Rh}(\text{CO})\text{H}(\text{PPh}_3)_3$ in toluene (1.4 mL) and stirred at room temperature under nitrogen atmosphere for 10 minutes. The proper olefin was added in one portion and the mixture was pressurized with syngas and irradiated with microwaves for 20 minutes at 75 °C. After reaction the tube was cooled and the internal gas released. The reaction mixture was filtered, to recover heterogeneous NiX-

HBPAO **1b**, washed with C₆H₁₄ (2 X) and the filtrate evaporated under reduced pressure.

The crude mixture was further purified by flash chromatography when necessary. The spectroscopic data of the prepared aldehydes can be found in the supporting information.

2.4. Leaching experiment

NiX-HBPAO **1b** (105 mg, 0.081 mmol) was added to a solution of Rh(CO)H(PPh₃)₃ (100 mg, 0.11 mmol) in toluene (2 mL). The mixture was pressurized with syngas (4.8 bar) and irradiated with microwaves for 20 minutes, at 75 °C (max power 150 W). The tube was cooled and the internal gas released. After centrifugation (3500 rpm, 1 min, 25 °C) the solvent was removed and the catalyst washed with toluene (1 mL X 10), centrifugated and the solvent removed, the procedure was repeated for consecutive 5 times. The solutions collected were evaporated and the rhodium quantity determined by ICP analysis. After drying the catalyst overnight, the solid was suspended in toluene (2 mL). The mixture was pressurized with syngas (4.8 bar) and irradiated with microwaves for 20 minutes, at 75 °C (max power 150 W). The tube was cooled and the internal gas released. After centrifugation (3500 rpm, 1 min, 25 °C) the solvent was removed and the catalyst washed with toluene (1 mL X 5), centrifugated and the solvent removed, the procedure

was repeated for consecutive 5 times. The solutions collected were evaporated and the rhodium quantity determined by ICP analysis to check if rhodium leaching was still observed. The preformed solid catalyst (loading 0.01 mmol/g, 70 mg, 0.0007 mmol) was suspended in toluene (0.3 mL). 1-octene (5.6 μ L, 0.035 mmol) was added in one portion and the mixture was pressurized with syngas (4.8 bar) and irradiated with microwaves for 20 minutes, at 75 °C (max power 150 W). The tube was cooled and the internal gas released. After centrifugation (3500 rpm, 1 min, 25 °C) the solvent was removed and the catalyst washed with toluene (1 mL X 5), centrifugated and the solvent removed 5 times. The solutions collected were evaporated and the conversion determined by GC analysis. The catalyst was dried under vacuum over-night and used for additional 4 times, in the same reaction conditions.

3. Results and discussion

The overall procedure to immobilize NiXantphos on the HBPAO support is shown in Scheme 1. Two different A₂ isatin based monomers, **2a** and **2b**, were used to investigate the possible influence of the length of the spacer between the support and catalytic core

on the regioselectivity of the hydroformylation reaction. Both bromoalkyl-HBPAO (Br-HBPAO) **4a** and **4b** were prepared via the superelectrophilic arylation of the A₂ monomers **2a** and **2b** respectively with the B₃ monomer (**3**) and the synthesis has been performed with more accessible CH₃SO₃H instead of the more costly and more toxic CF₃SO₃H.⁵⁷⁻⁵⁸

The optimization of the synthesis of **4b** is summarized in table 1 while data for compound **4a** are available in SI. The molecular weight increases proportionally by increasing the temperature and/or the reaction times. Residual peaks of oligomers and/or monomers decrease (Figure S1). The polymer was formed after 48 h at 50 °C (Table 1, entry 5). The molecular weights reported in table 1 are an underestimation since these were determined by gel permeation chromatography (GPC) calibrated with linear poly(methyl methacrylate) standards. The absolute molecular weight of **4b** was found to be higher (M_w = 15870) with a PDI of 1.59 as determined by GPC-Multi angle light scattering (MALS). Additional proof of the polymerization was obtained by comparing ¹H NMR spectra of both the A₂ monomer **2b** and B₃ monomer **3** with Br-HBPAO **4b** (Figure S2 and S3). Broadened signals are observed in the aromatic region of the Br-HBPAO **4b** spectrum corresponding to similar signals in the spectra of the monomers. The loading

of bromide in **4b** was determined by Total Reflection X-Ray Fluorescence (TXRF) being 1.34 mmol/g (Table S1).

Table 1. Superelectrophilic arylation.^a

Entry	Temperature (°C)	Time (h)	GPC-UV Calibrated with Polystyrene ^b		
			Mw (kDa)	Mn (kDa)	PDI
1	rt	48	5	4	1.25
2	40	48	7	5	1.42
3	50	7	5	4	1.27
4	50	16	7	5	1.41
5	50	48	8 ^c	5	1.69 ^c

^aReaction conditions: **2b** (0.15 mmol), **3** (0.15 mmol), CH₃SO₃H (0.05M). ^bResults obtained from GPC data shown in Figure S1. ^cMw = 16 kDa and PDI = 1.59 determined by GPC-MALS.

Scheme 1. Synthesis of HBPAO support and NiX-HBPAO **1a** and **1b**.

Br-HBPAOs are readily prepared in a one-step polymerization. Br-HBPAO are hydrophobic, in contrast to commercial HBPs (e.g. polyethylenimine), and easily purified. Polymer functionalization plays a major role for achieving highly defined macromolecular structures with a wide variety of material properties. Br-HBPAO contain predefined reactive bromide groups with an adjustable linker. Herein we present the functionalization with NiXantphos, however modification with other molecules could lead to functional materials with different applications.⁴⁶

The sodium salt of NiXantphos **5** ($\text{pK}_a \sim 22$) was generated using NaH.⁵⁹ A solution of Br-HBPAO **4** was added to this reactive nucleophile and stirred overnight to generate NiX-HBPAO **1** (details for both **1a** and **1b** in SI). NiX-HBPAO **1b** was analyzed by ^1H and ^{31}P NMR in solution of CDCl_3 . The analysis was possible only at very low concentration

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3 because of the poor solubility of **1b** in CDCl₃, DMF and DMSO-d₆. Moreover, relevant
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7 information has been obtained from these analyses observing diagnostic peaks at 6.5-
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10 6.0 ppm, directly related to the presence of NiXantphos (Figure S4 and S5). Three distinct
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13 shifted signals of a propyl linker are detected in the alkyl region. The substitution of the
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16 reactive bromides by NiXantphos was confirmed by ³¹P NMR spectrum of **1b** showing a
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21 peak at -18.8 ppm, corresponding to the chemical shift of NiXantphos, (Figure 2).⁶⁰
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Figure 2. ^{31}P -NMR spectrum of **1b** (A) ^{31}P -NMR spectrum of a 1:1 mixture of **1b** and NiXantphos **5** (B).

Br-HBPAO **4b**, and NiX-HBPAO **1b** were further analyzed by FT-IR (Figure S6) observing new bands in the lower region (1713 until 492 cm^{-1}) that are also present in NiXantphos **5** spectrum contemporary with the disappearance of the secondary amine *N*-H band at 3406 cm^{-1} .

Thermo Gravimetric Analysis (TGA) trace of **4b** differs from TGA trace of **1b** (Figure S8). Both show a first weight loss at 300 °C however the weight loss is higher for **1b** than **4b**. A second and final degradation of the HBPAO support is observed at 500 °C for both. TGA analysis demonstrates that **4b** and **1b** are thermally stable since decomposition occurs at high temperature (> 300 °C). The thermal stability is a key promising parameter for catalyst recycling. The GPC chromatograms (Figure 3) have a different profile indicating a change in hydrodynamic volume due to the post functionalization. GPC-MALS analysis of **1b** in THF was impossible due to its insolubility. Based on the absolute molecular weight of **4b** we can however conclude that the lower limit in molecular weight of **1b** is 16 kDa and increases substantially due to the large difference in molecular weight between bromide and NiXantphos.

The loading of NiXantphos grafted on HBPAO was determined by determining the difference in nitrogen content in **4** and **1** by CHN elemental analysis: a loading of 0.68 mmol/g for **1a** and 0.84 mmol/g for **1b** was obtained. Secondly a ³¹P qNMR with an internal standard resulted in a similar loading of 0.61 mmol/g for **1a** and 0.77 mmol/g for **1b**.

Figure 3. GPC-UV trace at 254 nm of Br-HBPAO **4b** (solid line) and of NiX-HBPAO **1b** (dashed line) in THF:DMF (1:1) + 0.05 M LiBr.

We have selected 1-octene as a model substrate to optimize the microwave assisted heterogeneous hydroformylation protocol using **1a** and **1b** as the supported ligands. On the basis of our previous findings in microwave assisted hydroformylation, carbonylhydridotris(triphenylphosphine)rhodium ($\text{Rh}(\text{H})\text{CO}(\text{PPh}_3)_3$) and Xantphos are the optimal catalyst and ligand for a complete and fast transformation, showing good regioselectivities towards linear aldehydes.²¹ The previously reported optimal conditions with $\text{Rh}(\text{H})\text{CO}(\text{PPh}_3)_3$, irradiation with microwave at 110 °C for 10 minutes in the presence of 4.8 bar of syngas (1:1 mixture $\text{CO}:\text{H}_2$) was investigated with heterogeneous **1a** and **1b** instead of Xantphos. In these conditions, the double bond hydrogenation producing

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3 octane (**7**) occurs as the main reaction pathway (Table S3). Contrary to the homogeneous
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7 protocol, which required high temperatures (110 °C), by lowering the reaction temperature
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10 to 75 °C the aldehyde **8** was observed for the heterogeneous protocol.
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14 A 'blank' test reaction using $\text{Rh(H)CO(PPh}_3)_3$ without any homogenous or
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17 heterogeneous ligand and irradiating with microwaves at 75 °C for 20 minutes in the
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20 presence of 4.8 bar of syngas gave **7** as the only reaction product (Table 2, entry 1).
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24 Similar results were obtained using Xantphos as the ligand in the same reaction
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27 conditions (Table 2, entry 2). Under the microwave conditions used, mild reaction
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30 temperature and pressure favor hydrogenation over hydroformylation catalyzed by
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33 rhodium.⁶¹⁻⁶³ However we cannot exclude the formation of a highly hydrogenation-active
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38 rhodium species (e.g. rhodium nanoparticles) under microwave irradiation resulting in
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41 rapid hydrogenation which out-competes the hydroformylation. We first evaluated NiX-
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45 HBPAO **1a**, expecting a low influence of the HBPAO support and the catalytic core
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48 because of the long linker present. The first experiment with **1a** gave poor conversion
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51 and, again, the undesired octane **7** as the main reaction product (Table 2, entry 3).
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56 Conversion increased by both increasing the temperature and decreasing the time of
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3 irradiation; however still only undesired **7** was obtained (Table 2, entry 4). By increasing
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6 the ligand to catalyst ratio to 16 to 1, we observed the formation of **8**, but the conversion
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9 was still low and undesired **7** was still formed (Table 2, entry 5). Maintaining this ligand to
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12 catalyst ratio and solely increasing the pressure of syngas to 6.2 bar, the conversion
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15 increased, but again only **7** was formed (Table 2, entry 6). We have to keep the presence
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18 of a competing *in situ* formed hydrogenation catalyst influencing the results as plausible.
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21 By increasing reaction time and lowering the pressures of syngas to 4.0 bar at a ligand to
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24 catalyst ratio of 8 to 1 we avoided the formation of undesired octane and the aldehyde **8**
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27 was obtained in moderate yield of 57% (Table 2, entry 7). However, to our
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30 disappointment, no regioselectivity towards the linear **8a** nor the branched product **8b**
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33 was observed. We also ran the reaction using ethanol as the solvent: unfortunately,
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36 mostly hydrogenation and no regioselectivity for the hydroformylation product was
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39 observed (Table S3). At this point we decided to investigate NiX-HBPAO **1b** which has a
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42 shorter linker between the support and the catalytic core. Our first attempt, to our delight,
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45 immediately gave far better results: in only 20 minutes using 4.8 bar of syngas, a 95%
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48 conversion into the linear aldehyde **8a** (85% isolated yield) was achieved with just traces
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3 of the branched **8b** as the only side product (Table 2, entry 8). Next, we tried to lower the
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7 irradiation time to 4 min and a decrease in conversion was observed (Table 2, entry 9).
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10 However, the desired aldehydes herein are still rapidly obtained by using microwave
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13 irradiation at low temperature with respect to ordinary catalytic systems. Based on the
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17 reaction outcome (Table 2, entry 8 vs entry 1 and 2) we observe a different activity for our
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21 heterogeneous catalyst. The observed hydroformylation activity for both NiX-HBPAO **1a**
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24 and **1b** confirms activity happening at catalytic sites within the HBPAO network (Table 2,
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28 entry 7 and 8). The observed difference in aldehyde ratio could result from a different
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32 catalytic environment and thus activity. NiX-HBPAO **1a** and **1b** are prepared from
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35 monomers **2a** and **2b** having different linkers thus affecting polymerization and leading to
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39 a different three-dimensional network with different organization of catalytic sites.
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42 Regarding the observed hydrogenation activity, we cannot exclude the leaching of
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46 rhodium in combination with microwave irradiation giving rise to hydrogenation active
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49 species that affect the results (Table 2, entry 1-6). The remarkable activity of our
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53 heterogeneous catalyst under mild conditions could arise from a dendritic effect. While
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56 the exact origin is unknown a cooperative effect similar to the report of Alper *et al.* in the
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HBPAO three-dimensional network might arise.⁴⁴⁻⁴⁵ Homogeneous rhodium binuclear catalysts are reported for the hydroformylation under milder conditions due to a cooperative effect.⁶⁴⁻⁶⁵ Stanley *et al.* proposed an intramolecular hydride transfer, between two rhodium centers in close proximity, which facilitates the elimination of the aldehyde from the acyl intermediate.⁶⁴ Hydride transfer between two rhodium centers in the dendritic three-dimensional network could indeed be favored also in our case. The dendritic effect could also be attributed to strong binding of rhodium within the three dimensional HBP network. Strong binding avoids the leaching of rhodium that might influence the results by forming active rhodium species. More detailed studies, outside the scope of this work, are necessary to further elucidate the remarkable effectiveness of our catalyst.

Table 2. Optimization of microwave assisted hydroformylation protocol with heterogeneous ligand.^a

Entry	Ligand	7 (%) ^b	8 (%) ^b	8a:8b ^b	C (%) ^b
1	-	98	-	-	>99
2	Xantphos	98	-	-	>99
3	1a	30	-	-	30
4 ^c	1a	83	-	-	83
5 ^d	1a	30	5	-	35
6 ^e	1a	70	-	-	70
7 ^f	1a	-	57	1:1	57
8	1b	-	95	15:1	95
9 ^g	1b	-	40	n.d.	40

^aGeneral conditions: **6** (0.04 mmol), **1a** or **1b** (16 mol%), Rh(H)CO(PPh₃)₃ (2 mol%) (8:1 ratio) in 1.4 mL toluene 20 min microwave at 75 °C under 4.8 bar CO:H₂ (1:1).

^bDetermined by GC with benzoquinone as internal standard and ¹H NMR. ^c4 min microwave at 110 °C. ^d**1a** (32 mol%), Rh(H)CO(PPh₃)₃ (2 mol%) (16:1 ratio). ^e**1a** (32 mol%), Rh(H)CO(PPh₃)₃ (2 mol%) (16:1 ratio) under 6.2 bar. ^f30 min microwave at 75 °C under 4.0 bar. ^g4 min microwave at 75 °C under 4.8 bar. n.d. = not determined and C = conversion.

The process demonstrates to be heterogeneous as the catalyst has been reused for 5 times in the hydroformylation of 1-octene without the subsequent addition of more rhodium complex or changing the catalyst to substrate ratio. A further evidence that the process occurs in heterogeneous phase is represented by the complexation of NiX-

HBPAO **1b** with rhodium at 60 °C under microwave irradiation for 10 minutes. After centrifugation, filtration and washing the catalyst to remove any non-complexed rhodium, the rhodium supported catalyst was used in the hydroformylation of 1-octene and, after centrifugation and filtration, the filtrate was analyzed by ICP-MS after each run and the catalyst reused. Over the five runs high conversion and a regioselectivity of 15:1 was obtained proving the reusability of the supported catalyst. The amount of rhodium leached was slightly higher in the first run compared to the next four (Table 3).

Table 3. Recovery and reuse of NiX-HBPAO **1b** in hydroformylation of 1-octene.^a

Run	Conversion ^b	I:b ^b	Leached Rh ^c
Run 1	95%	15:1	2.81 ppm
Run 2	93%	15:1	0.25 ppm
Run 3	94%	15:1	0.22 ppm
Run 4	92%	15:1	0.19 ppm
Run 5	92%	15:1	0.17 ppm

^a1-octene (0.035 mmol), **1b** with Rh complexed in 0.3 mL toluene 20 min microwave at 75 °C under 4.8 bar CO:H₂ (1:1). ^bDetermined by GC with benzoquinone as internal standard and ¹H NMR. ^cDetermined by ICP-MS.

The use of **1b** in ratio 8 to 1 with respect to the Rh catalyst, with 4.8 bar of syngas and a reaction time of 20 min of microwave irradiation at 75 °C were selected as the optimal hydroformylation conditions to be used on more complex substrates as summarized in scheme 2. Excellent results were observed for ethyl pent-4-enoate, forming the desired linear aldehyde **18** in 85% of isolated yield without the formation of any branched or hydrogenated side product. Allylbenzene was converted to 4-phenylbutanal **19** with good selectivity and in moderate yield with only trace amounts of hydrogenation product observed. Hydroformylation of limonene to the linear aldehyde **20** was unsuccessful, mostly starting material and a small amount of branched aldehyde were observed. Branched olefins, including limonene, are less reactive due to increased sterical hindrance,²² thus we tried to increase the reaction temperature and pressure of syngas but no significant improvement was observed (Table S5).

When applying the optimized conditions on the substrate *N*-allylphthalimide, we observed the formation of the desired aldehyde **21**, however equal amounts of hydrogenated side product were formed. The formation of the hydrogenated side product was suppressed (by 25%) and the formation of the desired aldehyde **21** increased (by

27%) by increasing the supported ligand to rhodium ratio and decreasing the syngas pressure. Both the amide (aldehyde **22**) and trimethylsilyl (aldehyde **23**) functionality were tolerated, resulting in the desired aldehyde in good to excellent yields without the formation of side products. A surprising result was obtained using styrene and 4-vinylphenyl acetate: the linear aldehydes **24** and **25** were formed as the main reaction product in acceptable yields. Styrene (and 4-vinylphenyl acetate) usually is converted into the branched aldehyde due to the stability of the benzylic rhodium η^3 complex in homogenous conditions⁶⁶ even using Xantphos under microwave conditions.²¹ A reverse regioselectivity of styrene has been previously observed with the use of enzymes as support.⁶⁷⁻⁶⁹ The reverse selectivity is attributed to a specific microenvironment. A similar steric crowding in a dendritic three-dimensional network can influence the catalytic performance.⁷⁰⁻⁷¹ The reverse regioselectivity further confirms the influence of the HBPAO support. *N*-vinyl imidazole did not give rise to the desired aldehyde **26**, instead the hydrogenation side product was formed even at higher supported ligand to rhodium ratio, lower pressures of syngas and irradiating for shorter reaction times or higher temperature (Table S5). The results presented illustrate the compatibility of the protocol

with different functionalities (i.e. imides, esters, amides, trimethylsilyl groups) but it also shows a strong influence of the starting material on the outcome of the reaction (aldehyde **18** compared to the desired aldehyde **20** for example). These findings clearly show that the outcome of each reaction needs to be evaluated on a per case basis. Nevertheless, heterogeneously catalyzed hydroformylation protocols reported so far are usually applied to unfunctionalized olefins only, thus limiting possible comparison and benchmarking. The functional group tolerance we show confirms the value of this catalytic system.

Scheme 2. Hydroformylation scope.^a

^a**9-17** (0.04 mmol), **1b** (16 mol%), Rh(H)CO(PPh₃)₃ (2 mol%) (8:1 ratio) in 1.4 mL toluene 20 min microwave at 75 °C under 4.8 bar CO:H₂ (1:1). ^bConversion determined by GC

with benzoquinone as internal standard. ^cIsolated yield. ^dRatio l:b aldehyde determined by ¹H NMR. ^e**1b** (32 mol%), Rh(H)CO(PPh₃)₃ (2 mol%) (16:1 ratio). ^f**1b** (32 mol%), Rh(H)CO(PPh₃)₃ (2 mol%) (16:1 ratio) under 4.0 bar CO:H₂ (1:1). l:b ratio homogeneous conditions in brackets in green for **24** and **25**.²¹

To demonstrate the general applicability of the developed heterogeneous NiX-HBPAO **1b** in other transformations than hydroformylation, we investigated its use in a carbonylation reaction. In fact, Xantphos has shown excellent results in the palladium catalyzed aminocarbonylation of aryl bromides for the synthesis of Weinreb amides, benzamides and methyl esters at atmospheric pressure.⁷² Xantphos and NiXantphos have shown similar activity thus we decided to test **1b** in the palladium catalyzed aminocarbonylation. A similar protocol as reported by Buchwald *et al.* was used (Scheme 3). Similar isolated yields after a single run were obtained for NiX-HBPAO **1b** and Xantphos but the supported catalytic complex was recovered by precipitation. The application of **1b** in the palladium catalyzed coupling proves the diverse potential of this heterogeneous catalyst and further evaluation is ongoing.

Scheme 3. Aminocarbonylation with heterogeneous NiX-HBPAO **1b** and homogeneous Xantphos.

4. Conclusion

The potential of HBPAO as support for phosphine ligands was explored. Br-HBPAOs, with diverse linkers, were prepared via superelectrophilic reaction of an A₂ + B₃ monomer.

The Br-HBPAOs were prepared in a one-step polymerization and contain reactive bromide groups, which are substituted with NiXantphos, without needing any further reactions. The simple two-step polymerization/post-modifications are a convenient procedure for the synthesis of the supported ligand. The supported ligands NiX-HBPAO were characterized and evaluated in the rhodium catalyzed, microwave assisted hydroformylation of olefins and the palladium catalyzed aminocarbonylation of bromobenzene. For the hydroformylation excellent regioselectivity was obtained for 1-octene in very mild reaction conditions in terms of temperature, time and syngas pressure. Moreover, several complex substrates containing various functional groups were tested, selectively forming the desired linear aldehydes in distinct substrates even starting from

styrene derivatives, thus indicating a reverse regioselectivity with respect to the homogeneous reaction. The mild conditions and reverse regioselectivity in the hydroformylation might emanate from the unique dendritic nature of the support resulting in a positive dendritic effect. Furthermore, the catalytic system was successfully recovered and reused without any decrease in conversion or selectivity. The solid supported NiX-HBPAO here developed can be considered as a promising system for many other heterogeneous transformations involving Xantphos as the ligand.

ASSOCIATED CONTENT

Additional figures, synthetic and experimental procedures, tables with experimental data and analysis (PDF)

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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(72) Martinelli, J. R.; Watson, D. A.; Freckmann, D. M. M.; Barder, T. E.; Buchwald, S. L. Palladium-Catalyzed Carbonylation Reactions of Aryl Bromides at Atmospheric Pressure: A General System Based on Xantphos. *J. Org. Chem.* **2008**, *73*, 7102-7107.

TOC figure

Structures of heterogeneous ligand **1a**, **1b** and homogeneous ligand Xantphos.

196x43mm (300 x 300 DPI)

Synthesis of HBPAO support and NiX-HBPAO 1a and 1b.

354x160mm (300 x 300 DPI)

^{31}P -NMR spectrum of 1b (A) ^{31}P -NMR spectrum of a 1:1 mixture of 1b and NiXantphos 5 (B).

GPC-UV trace at 254 nm of Br-HBPAO 4b (solid line) and of NiX-HBPAO 1b (dashed line) in THF:DMF (1:1) + 0.05 M LiBr.

Optimization of microwave assisted hydroformylation protocol with heterogeneous ligand.a

142x24mm (300 x 300 DPI)

160x154mm (300 x 300 DPI)

19 Aminocarbonylation with heterogeneous NiX-HBPAO **1b** and homogeneous Xantphos.

20 163x60mm (300 x 300 DPI)

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