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A water-based and high space-time yield synthetic route to MOF Ni$_2$(dhtp) and its linker 2,5-dihydroxyterephthalic acid.

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2,5-dihydroxyterephthalic acid (H$_4$2dhtp) was synthetized in a 18g2scale by carboxylation of hydroquinone in molten potassium formate. The hydrated form of Ni$_2$(dhtp) MOF (also known as CPO-27-Ni and MOF-74(Ni)), was obtained in 92% yield by refluxing for 1h a water suspension of the H$_4$2dhtp linker with an aqueous solution of nickel acetate. The ensuing characterization of the material (XRD, HRTEM, TGA, N$_2$ adsorption at 77K - $S_{BET} = 1233$ m$^2$/g) confirmed the obtention of a metal-organic framework of at least equal quality than the ones obtained from the previously reported routes (CPO-27-Ni and MOF-74(Ni)), with a different morphology (namely, well-separated 1 µm platelets for the herein reported water-based route). The temperature dependence of the magnetic susceptibility was measured and satisfactorily simulated assuming a Heisenberg ($H = -2\sum S_i S_{i+1}$) ferromagnetic intrachain interaction ($J = +8.1$ cm$^{-1}$) with antiferromagnetic interchain interaction ($J' = -1.15$ cm$^{-1}$). Overall, the reaction in water appears to follow easily distinguishable steps, the first being the deprotonation of H$_4$2dhtp by acetate counterion, leading to a soluble nickel adduct of the linker, en route to the MOF self-assembly.

Introduction

Metal-Organic Frameworks (MOFs) have received considerable attention over the past decade, especially in the field of gas purification and storage as well as catalysis and drug delivery. The growing interest for these materials recently led to the first industrial production of MOFs with the ton-scale synthesis of aluminum fumarate (Basolite A520®) at BASF facilities which is a promising candidate for methane storage and delivery. This transfer to industrial production has been achieved, inter alia, through the development of a water-based route, reducing both production costs and environmental impact while increasing the production rates. Unfortunately, entirely water-based MOF synthesis are still very limited.

Among the wide diversity of MOFs, the M$_2$(dhtp) series (dhtp = dobdc = 2,5-dioxido-1,4-benzenedicarboxylate [O$_2$C-C$_6$H$_4$O$_2$-CO$_2$]$^+$; M = Mg, Mn, Fe, Co, Ni or Zn)$^7$, called CPO-27-M (CPO = Coordination Polymer of Oslo) or MOF-74(M), has been extensively studied because of its 1D microporous hexagonal channel structure with calibrated pores at 12 Å which allow an optimal interaction between the walls of the solid and guest molecules. In fact, M$_2$(dhtp) offers a permanent porosity upon solvent removal, displaying strong adsorption centers at the penta-coordinated open metal sites (see Scheme 1 for M = Ni) which allow the selective adsorption/desorption of a wide diversity of molecules without loss of porosity.$^8$-10 In particular the nickel member of the M$_2$(dhtp) series, which is highly tolerant towards moisture and oxygen,
reversibly adsorb sulfur-containing molecules like H$_2$S$^{15}$ or thiophene$^{14}$, perform the selective adsorption of CO and CO$_2$ over CH$_4$ and H$_2$$^{9,10}$ and of CO$_2$ over N$_2$ even under 3% relative humidity$^{15}$ while the efficiency of this separation using Mg$_2$(dhtp) or zeolites is much more affected by only trace amount of water$^{16,17}$. Most strikingly, Ni$_2$(dhtp) methane storage capacity is among the highest reported for MOFs (214 cm$^3$(STP)/cm$^3$ at 25°C, 35 bars)$^{18}$, which makes it a very promising candidate for adsorption and/or separation applications. Ni$_2$(dhtp) is also active as Lewis-type catalyst$^{19}$ and its use for delivering an anticancer drug$^{20}$ as well as its use in antimicrobial NO-delivering patch$^{21}$ has been reported.

Overall, MOF syntheses, there included Ni$_2$(dhtp) synthetic routes reported so far$^{12,22,23}$ (see results section below for details), require high dilution factors which imply large amounts of organic solvents, low production rates and strong environmental impact. This is mainly ascribed to the difficulty to find a good solvent for both the metal salt and the organic linker. Therefore, not optimized small-scale lab syntheses as described in the literature have usually space-time yields (STY) between 0.1 and 1 kg/m$^3$/day or even lower$^{10}$. While reaction time has been reduced by one order of magnitude using ultrasounds or microwave heating$^{24}$, the minimization of solvent usage is still a goal to attain with a STY larger than 500 kg/m$^3$/day. Beyond this, the development of water-based routes for MOF synthesis would strongly facilitate their industrialization. Indeed, organic solvents are more difficult to use at industrial levels because they shall be handled in specific non-flammable area, while water is a cheap, safe and more easily post-treatable solvent.

Here we report for the first time the synthesis of Ni$_2$(dhtp) in water with high space-time yield. We carefully demonstrate the quality of the obtained Ni$_2$(dhtp) by a series of characterization at short and long range, as well as its porous structure and not yet reported magnetic properties. In addition, we describe a synthesis method in a single step of the H$_4$dhtp linker from hydroquinone (which is a bulk chemical) using a cheap and organic solvent-free procedure. Indeed, 2,5-dihydroxyterephthalic acid is distributed in gram scale by different chemical suppliers at a price of about $15 per gram. Although it does not represent the price at industrial level, it strongly limits its synthesis at kg scale for demonstration purposes.

**Results and discussion**

Two different synthetic routes have been reported for the isomorphous family of M$_2$(dhtp), both of them requiring organic solvents: tetrahydrofuran (THF) for the CPO-27 material originated from SINTEF’s work in Oslo$^{22}$ and dimethylformamide (DMF) (or DMF/water or DMF/water/ethanol mixtures) for the MOF-74$^{23}$ developed by Yaghi’s group. The general procedure consists in mixing an aqueous solution of the metal salt with a solution of 2,5-dihydroxyterephthalic acid in the appropriate organic solvent inside a Teflon-lined autoclave, followed by heating at the appropriate temperature (ca. 100-110°C) for 2-3 days. The use of dimethylformamide generally reduces both temperature and reaction time$^{25}$ but the resulting MOF then have to be washed several days with methanol because of the strong coordination of DMF molecules to the framework nickel atoms, which prevents simple removal by vacuum treatment. If the tetrahydrofuran/water mixture is used, relatively large amount of solvents are required as well as long reaction times: in a typical procedure$^{12}$, three days at 110°C were necessary to produce 6.46 g of CPO-27-Ni (4.10 g expected after complete water removal) from 100 ml of a THF/Water (1:1) mixture.

The procedure described here for the synthesis of Ni$_2$(dhtp) entails only concentrated aqueous solution under atmospheric pressure, without the addition of organic co-solvent at any point of the procedure.

### H$_4$dhtp synthesis

2,5-dihydroxyterephthalic acid has been directly synthetized in good yields from the inexpensive hydroquinone using an organic solvent-free procedure (see Scheme 2), derived from a patented process$^{26}$ and adapted for laboratory-scale experiment by replacing pressurized CO$_2$ with an atmospheric-pressure
CO₂ stream. Preformed potassium formate has also been replaced by its in situ generation from K₂CO₃ and HCOOH to yield the molten salt reaction medium. The yellow crystalline 2,5-dihydroxyterephthalic acid can be conveniently recovered by filtration after acidification of the reaction crude and washings by water, and used directly for the MOF synthesis.

**Ni₂(dhtp) synthesis**

The procedure for Ni₂(dhtp) synthesis consists in mixing an aqueous solution of nickel (II) acetate (warmed at 80°C to allow high concentration of the metal, typically 1M) with a suspension containing 1.02 equivalent of 2,5-dihydroxyterephthalic acid in water (ca. 25 g/L). Upon adding the nickel-containing solution to the linker suspension, the reaction mixture immediately turns into a clear emerald green solution. When this solution is heated at reflux temperature, a yellow solid quickly precipitates. After 1h-reflux, washing with water and drying at 80°C, the final product is recovered as a yellow solid with almost full conversion with respect to the nickel salt, the limiting reagent of the procedure (calculated yield : 91.6%).

**X-Ray Diffraction**

The X-ray powder diffraction (XRD) pattern of the product after full rehydration shows a highly crystalline material (see Figure 1 for experimental and simulated diffractograms).

![Figure 1: View of the experimental powder XRD pattern (red dots) and the simulated one (black line) by the Le Bail method. The difference curve is shown in blue.](image)

The highest intensity peaks of the material obtained from the aqueous procedure are found at 2θ = 6.80° and 11.79° (corresponding to d₃₄₀ = 12.99 Å and 7.48 Å). These measurements are in good agreement with the published CPO-27-Ni crystallographic data²² : 2θ = 6.80° and 11.79°, corresponding to d₃₄₀ = 12.99 Å and 7.50 Å, that is the (-120) and (030) planes, respectively. The X-ray powder diffraction pattern was fitted using Le Bail full profile fitting method²⁷ through the FullProf²⁸ and Winplotr²⁹ softwares. Figure 1 shows a good agreement between the recorded powder pattern (red) and the simulated one (black). No supplementary peaks were observed in the difference curve (blue) which confirms the purity of the obtained sample.

**Permanent microporosity**

The reversible N₂ adsorption and desorption performed at 77K (see Figure 2 and Figure S1) lead to specific surface areas of 1233 m²/g (Brunauer-Emmett-Teller (BET) method) and 1355 m²/g (Langmuir method), in line with the highest specific surface area of 1218 m²/g (BET method) reported in the literature for CPO-27-Ni material²². The adsorption/desorption isotherms are satisfactorily fitted with the NLDFT simulation method²⁰ (see Figure S1), which allows to obtain a pore size distribution plot (see inset Figure 2) with a mean pore diameter of 11.7 Å, in agreement with the calculated value of 11.85 Å²², and an estimated pore volume of 0.823 cm³/g.

**Magnetic susceptibility**

The magnetic behavior of the Co³¹ and Fe³² members of the M₂(dhtp) isomorphous family of MOFs has already been reported, but not, to the best of our knowledge for Ni₂(dhtp), for which only a theoretical investigation is available³³. At room temperature, the product of the magnetic susceptibility with the temperature (χT), of a fully rehydrated Ni₂(dhtp) obtained from the water based route, is 2.67 cm³.K.mol⁻¹. Upon cooling, χT increases and reaches the maximum value of 3.57 cm³/K mol⁻¹ at 20 K and then drops abruptly below this temperature. This behavior is in agreement with the ferromagnetic coupling of nickel (II) ions (S = 1) along the chain running parallel to the c axis, as previously observed for Co(II) and Fe(II) analogs³¹, ³². To extract the value of the magnetic interaction, the data were simulated for [Ni₂(dhtp)(H₂O)₂]·8H₂O assuming Heisenberg

![Figure 2: Experimental N₂ adsorption (blue diamonds) and desorption (purple squares) isotherms at 77K of Ni₂(dhtp) synthetized in aqueous solution; in the inset: calculated pore size distribution from simulated adsorption isotherm reported in Supplementary information. Figure S1.](image)
interactions between spins \((H=-(1/2)\Sigma S_i S_{i+1})\) using the Fisher analytical expression for the magnetic susceptibility of an infinite chain of classical spins \(S = 1\) with an interchain magnetic interaction in the molecular field approximation \((ZJ')\). The best fit (Figure 3A) gives a ferromagnetic intrachain interaction \(J = +8.1\ \text{cm}^{-1}\) and an antiferromagnetic interchain interaction \(J' = -1.15\ \text{cm}^{-1}\) with \(Z = 3\) as previously suggested and \(g = 2.02\). A small TIP has been included \((150.10^{+26}\ \text{cm}^{-1})\). At 2K the magnetization vs. magnetic field (Figure 3B) first increases linearly with the magnetic field. Then, around 2.8 T, a transition is observed, progressively moving towards the expected value for two nickel (II) ions \((\approx 2\mu_B)\). This field-induced transition may be ascribed to the fact that the small antiferromagnetic interchain interactions are overtaken by the strength of the magnetic field, in line with what has already been reported for the CPO-27-Co.

Thermal behavior

Thermogravimetric analysis under \(N_2\) of another aliquot of the \(\text{Ni}_2(\text{dhtp})\) material exposed to moist air at room temperature for thirty minutes displays both of the expected phenomena, namely: firstly a loss of water molecules present inside the pores of the MOF or coordinated to the nickel atom, phenomenon occurring up to 200°C and leading to the fully dehydrated phase, \(\text{Ni}_2(\text{dhtp})\), which is stable up to 360°C, and secondly the thermal decomposition of MOF material (see Figure S2 A). The water content estimated from the weight loss up to 200°C is equivalent to about 8 molecule of water per \(\text{Ni}_2(\text{dhtp})\), suggesting an almost complete rehydration of the sample toward its fully hydrated form \([\text{Ni}_2(\text{dhtp})(\text{H}_2\text{O})_2]\cdot8\text{H}_2\text{O}\) reported in the literature. As already reported, the thermogram obtained under \(O_2\) is quite similar, with decomposition occurring at lower temperature \((280°\text{ vs. }360°C\ \text{under }N_2,\ \text{see Figure S2 B}).

Morphology of the \(\text{Ni}_2(\text{dhtp})\) synthetized in water

The well-formed 1D channels of the \(\text{Ni}_2(\text{dhtp})\) material obtained from the aqueous synthetic route were observed by high-resolution transmission electron microscopy (see Figure 4A). The measured 12.5 Å distance between two contiguous lines observed in the micrograph can be explained as corresponding to the 12.99 Å spacing between two (-120) planes in the CPO-27-Ni crystallographic structure (see Figure S3).

At lower magnification, the micrographs showed platelets of about 1 µm width (see inset in Figure 4A), distinctively different in morphology with respect to the crystallites obtained by us following the CPO-27-Ni procedure (see Figure 4B).
This lower symmetry morphology with presence of agglomerates appears representative of the morphology induced by the CPO-27 route, based on the comparison with existing literature micrographs of CPO-27-Ni36. As recently reviewed,17 the existence of a correlation between the composition of the solvent mixture and the crystallinity, or the shape of the resulting MOF crystals has already been established for some MOFs. The use of water as a co-solvent in such strategy was directly addressed in a study on MIL-96(Al) shape-selected crystallities growth38. The solvent appears in most cases to act as a modulator of crystal nucleation processes. To the best of our knowledge, such phenomenon had not yet been observed for a member of the M2(dhtp) family.

Mechanistic considerations

Substantial interest also lies in understanding the mechanism by which the MOF self-assembles from the metal ion and the linker precursor99. While we are unable to account for the crystallization mechanism that underpins the synthesis of the Ni2(dhtp) in water, the observation of some intermediates during the synthesis appears facilitated by the mild conditions reported here. During the synthesis, we observed the complete dissolution of the otherwise sparingly soluble acid linker at room temperature (see Figure S4 A to C). We assign such dissolution to the deprotonation of 2,5-dihydroxyterephthalic acid (pKa estimated at ca. 2.2) by the acetate counterion of the nickel salt present in the aqueous solution (pKa of acetic acid = 4.76)40. If this emerald green mother solution is stored for few minutes at room temperature, pastel green crystals start precipitating (see Figure S4 D) whose X-ray diffraction pattern is different from that of CPO-27-Ni (see Figure S5). The final MOF can be observed only when the mixture is heated above ca. 80°C, and its formation is complete within 1h if the heating is carried out at 100°C (Figure S4 E).

Conclusions

In conclusion, we have reported a novel synthetic route to Ni2(dhtp): in water, under air, at atmospheric pressure, with high space-time-yield and from an affordable linker, therefore complementing this already well-remarked member of the MOFs materials family with an additional attractive feature. A pertinent parameter to compare the performance of the aqueous route described herein with respect to the previously reported ones in organic solvents is the space-time yield expressed in terms of isolated MOF weight / volume of solvent used / time unit10, 41, 42. While the total volume of all solvents used should be taken into consideration, the available published data allow to calculate this value only taking into account the volume used during the synthesis itself (and not the ones used for the washing steps). The procedure reported here yields a production rate of 28.5 g/L/h, that is a 50-fold increase with respect to the published route (0.6 g/L/h considering the weight of fully dehydrated Ni2(dhtp))22. Expressed in Kg/m³/day, the industrially pertinent unit, the space-time yield of the water-based route described here could be extrapolated to 680 Kg/m³/day; such figure should be considered only as a very high upper estimate, since we have tested our method only on a 18g-scale and have not included the time-intensive washing and drying steps necessary for the ton-scale batches. At the same time, such figure abodes well of the industrial potential of this route, given the reported industrial space-time yields of 160 Kg/m³/d for Basolite A100, 225 Kg/m³/d for Basolite C300 and over 300 Kg/m³/d for Basolite M05040, 41.

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Author Contributions

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Experimental Section

Materials and methods

Nickel (II) acetate tetrahydrate 99%, (Sigma-Aldrich), hydroquinone (Aldrich Chemie), anhydrous K2CO3 (Acros), formic acid 98% (Sigma-Aldrich) and HCl 37% (VWR Chemicals) were used without further purification.

Characterization techniques

Powder X-ray diffraction data were collected in the “Centre de Diffractométrie Henri Longchambon”, site CLEA, Villeurbanne, on Bruker D8 Advance Diffractometer (Cu Kα radiation, 33 kV, 45 mA). Diffraction data were recorded in the range of 4-70° 20. High-Resolution Transmission Electron Micrographs were performed at the “Centre Technologique des Microstructures”, UCBL, Villeurbanne, on Jeol 2100F Transmission Electron Microscope. The acceleration voltage was 200 kV. Scanning Electron Micrographs were performed at the “Centre Technologique des Microstructures”, UCBL, Villeurbanne, on FEI Quanta 250 FEG scanning electron microscope. Nitrogen adsorption/desorption measurements were carried out at 77K using a BELSORB-max from BEL JAPAN system. Before N2 adsorption, the samples were outgassed at 2.5*10⁻³ Pa ; 423 K for 3h. ¹H and ¹³C liquid NMR spectra were recorded on a Bruker DSX 300 NMR.
spectrometer. Magnetic-susceptibility data (2 - 300 K) were collected with a Quantum Design MPMS SQUID magnetometer under an applied magnetic field of 0.1 T on a powdered polycrystalline sample pressed in a PTFE sample holder equipped with a piston to avoid dehydration. The magnetization isotherm was collected at 2 K between 0 and 5 T. All data were corrected with the contribution of the sample holder and diamagnetism of the sample estimated with Pascal’s constants\(^1\). The analysis of magnetic data was carried out by simulation of \(\chi^T\) thermal dependence including an intramolecular interaction (J), an intermolecular interaction (\(J'\)) in the molecular field approximation and a temperature independent paramagnetism (TIP) according to the following expression:

\[
\chi = \frac{k_B^2 F(J,T)}{2kT-16\mu T}F(J,T) + \text{TIP}
\]

Where \(F(J,T) = \frac{2}{(1 + u)}\) and \(u = \frac{kT}{4J} - \coth \left( \frac{4J}{kT} \right)\).

Unless otherwise specified, all analyses were performed on fully rehydrated \(\text{Ni}_2(\text{dhtp})\) samples. The rehydration procedure consisted in exposing the material (previously dried at 80°C overnight and stored in dry box) to water-saturated air for 24h at room temperature.

**Preparation of 2,5-dihydroxyterephthalic acid from hydroquinone**

In a 500 ml 2-neck round-bottom flask equipped with a condenser, \(\text{K}_2\text{CO}_3\) (97.7 g, 0.7 mol) was introduced. Formic acid (42.3 g, 0.9 mol) was added drop by drop under robust magnetic stirring, releasing large amount of \(\text{CO}_2\) and causing a strong exothermicity. The mixture was then heated up to 210°C, leading to a thick melt of potassium formate, bicarbonate and carbonate. The condenser was then removed and the reactor flushed for 30 min with a continuous stream of argon. The argon line was then replaced by a 500ml round-bottom flask filled with 300 g of dry ice. Hydroquinone (22.2 g, 0.2 mol) was added in a single portion to the melt and the condenser was placed back on the top of the reactor. The reaction mixture was then vigorously stirred for 6h at 210°C under the \(\text{CO}_2\) stream generated by the dry ice. After 6h, the yellow reaction mixture was dispersed in 300 ml of boiling water, leading to a suspension of white crystals in a dark-brown solution. This suspension was cooled to RT and filtered. The off-white powder obtained was finally suspended in 200 ml of water and acidified with 40ml of \(\text{HCl}\) 37%, causing the suspension to turn canary yellow. This suspension was stirred for 1h, filtered and washed 3 times with 50 ml-portions of deionized water. The yellow product obtained was dried at 80°C, yielding 20.8 g (105 mmol, 52.5% based on hydroquinone) of 2,5-dihydroxyterephthalic acid which was characterized by \(^1\)H and \(^{13}\)C NMR spectroscopy (see Figure S6 A and B).

**Synthesis of \(\text{Ni}_2(\text{dhtp})\) in water**

In a 500 ml round-bottom flask equipped with a condenser, a suspension of dihydroxyterephthalic acid (10.31 g, 51 mmol) in deionized water (400 ml) was heated to reflux under strong magnetic stirring (oil bath at 160°C). In a separate flask, nickel acetate tetrahydrate (25.14 g, 100 mmol) was dissolved in deionized water (100 ml) at 80°C. The light green nickel solution obtained was dropped in one portion to the boiling dihydroxyterephthalic acid suspension under continuous stirring leading almost instantaneously to a homogeneous emerald green solution. After few minutes, a yellow precipitate started to form. The reaction mixture was further refluxed for 1h. The final suspension was filtered and the yellow microcrystalline powder washed three times with 100 ml-portions of warm deionized water before being dried overnight at 80°C. 17.90 g of this material were isolated and characterized by powder XRD, HRTEM and TGA. The microporosity was determined by \(\text{N}_2\) adsorption at 77K after activation of a 105.7 mg aliquot for 20h at 150°C ; 5.10\(^{-3}\)mbar. The weight loss observed during this activation process was used to determine the water content in the isolated material (4.42 water molecule per \(\text{Ni}_2(\text{dhtp})\) unit). Isolated yield: 91.6% based on 17.90 g of \([\text{Ni}_2(\text{dhtp})·4.42 \text{H}_2\text{O}]\).

**Notes and references**


Synopsis TOC

Highway to MOF Ni$_2$(dhtp)! 1-hour in boiling water under atmospheric pressure; a cheap synthesis of the linker is also reported.