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Triphenylpyridine Linkers

A New Synthetic Pathway to Triphenylpyridines via Cascade Reactions Utilizing a New Iron-Organic Framework as a Recyclable Heterogeneous Catalyst

Son H. Doan,[a] Nhu K. Q. Tran,[a] Phuc H. Pham,[a] Vu H. H. Nguyen,[a] Ngoc N. Nguyen,[b] Phuong T. M. Ha,[a] Shuang Li,[c] Ha V. Le,[a,c] Nhan T. H. Le,[a] Thach N. Tu,*[b] and Nam T. S. Phan*[a]

Abstract: A new iron-organic framework, VNU-22 {[Fe_3(BTC)-(BPDC)$_2$]•11.97H_2O}, constructed from BTC^{3-}, $BPDC^{2-}$ pillars and infinite $[Fe_3(CO_2)_7]_\infty$ rod SBU, was obtained. The VNU-22 was utilized as a heterogeneous catalyst in the synthesis of 2,4,6-triphenylpyridines via cascade reactions from acetophenones and phenylacetic acids with ammonium acetate as a nitrogen source. This transformation is new. The VNU-22 was more active in the cascade reactions than many homogeneous and heterogeneous catalysts. The framework catalyst was recovered and reutilized without an appreciable decline in its performance. To our best knowledge, this synthetic pathway to 2,4,6-triphenylpyridines was not previously reported, and would attract interests from the chemical industry.

Introduction

Pyridine derivatives have emerged as one of the most valuable privileged nitrogen-containing heterocycles,[1] widely found in a variety of bioactive natural products, pharmaceuticals, agrochemicals, chemosensors, and functional organic polymers.[2] 2,4,6-Triphenylpyridines have attracted significant interests, and several protocols have been developed for the synthesis of these heterocyclic structures. Han et al. previously reported a Cu(OTf)$_2$-catalyzed one-pot formation of 2,4,6-triphenylpyridines from acetophenones and toluenes.[3] Zhang et al. demonstrated a HOTf-catalyzed one-pot generation of these heterocycles from acetophenones and benzylamines.[4] Rohokale et al. synthesized 2,4,6-triphenylpyridines using a photoredox catalysis approach.[5] Recently, ketoximes have been explored in the synthesis of phenylpyridines.[6] Yi et al. reported a $FeCl_3$-catalyzed cyclization of benzaldehydes with ketoximes to achieve 2,4,6-triphenylpyridines.[7] Zhao et al. developed a $FeCl_3$-catalyzed synthesis of these structures from ketoximes and *N*,*N*-dialkylanilines.[8] Although fascinating results have been achieved, new pathways to access these heterocycles remain to be investigated.

Metal-organic frameworks (MOFs) are highly crystalline and self-organizing reticular structures, consisting of metal nodes or clusters, interconnected by multifunctionalized organic linkers.[9] The flexibility with which the linkers and the metal-containing units could be diversified has led to the formation of a large variety of frameworks.[10] These networks have been considered as highly versatile materials that find applications in many fields.[11] Exclusive properties such as large surface areas, changeable pore size, and structural diversity have introduced MOFs to catalysis community.[12] Albeit a long series of MOFs have been published with detailed data on characterizations, their application in catalysis are yet limited.[13] Among numerous MOFs, iron-based frameworks have gained noticeable interests.[14] However, most of these Fe-MOFs possess oxo-centered trimers of octahedral Fe^{III} SBUs,[14b] and certainly, MOFs containing Fe^{II}-based SBUs are less well-known.[15] In this research, we would like to report the synthesis of a new iron-organic framework, named VNU-22. Structural analysis verified that this framework, with the formula of [Fe_3(BTC)(BPDC)$_2$]•11.97H_2O (BTC^{3-} = 1,3,5-benzenetricarboxylate; $BPDC^{2-}$ = 4,4′-biphenyldicarboxylate), composed of BTC^{3-} and $BPDC^{2-}$ pillars and the $[Fe_3(CO_2)_7]_\infty$ rod SBU. Moreover, the VNU-22 demonstrated high catalytic activity for a new pathway to triphenylpyridines via cascade reactions between acetophenones and phenylacetic acids with ammonium acetate as a nitrogen source.

Results and Discussion

Synthesis and Characterization of VNU-22

Structural analysis indicated that VNU-22 adopt the same topology with VNU-20 material.[16] Particularly, this material crystal-

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[a] *Faculty of Chemical Engineering, HCMC University of Technology, VNU-HCM,*
268 Ly Thuong Kiet, District 10, Ho Chi Minh City, Vietnam
E-mail: ptsnam@hcmut.edu.vn
[b] *Center for Innovative Materials and Architectures, VNU-HCM,*
Quarter 6, Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam
E-mail: tnthach@inomar.edu.vn
[c] *Institute of Chemistry–Functional Materials, Technische Universität Berlin, BA2,*
Hardenbergstraße 40, 10623 Berlin, Germany

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lized in the orthorhombic space group, *Pbcn* (No. 60), with larger unit cell parameters, a = 25.08246, b = 28.16846, and c = 13.73363 Å. Specifically, VNU-22 is built from the sinusoidal $[Fe_3(CO_2)_7]_\infty$ iron-rod SBU, which consisted of three consecutively distinct octahedral iron centers and connected each other through the sharing edge and vertex (Figure 1b). The sinusoidal $[Fe_3(CO_2)_7]_\infty$ iron-rod metal cluster is finally stitched by $BPDC^{2-}$ and BTC^{3-} linker (Figure 1a, Figure 1e, Figure 1f) to form VNU-22 (1 c, d). Certainly, the replacement of the H_2NDC by H_2BPDC linker directly resulted in the isoreticular expansion of VNU-22. This leads to the formation of a rectangular channel of 8.0 × 8.6 Å^2 constructing from thick walls architecture, composed of infinite rings to rings π–π interaction of $BPDC^{2-}$ linkers (Figure 1c, Figure 1f).

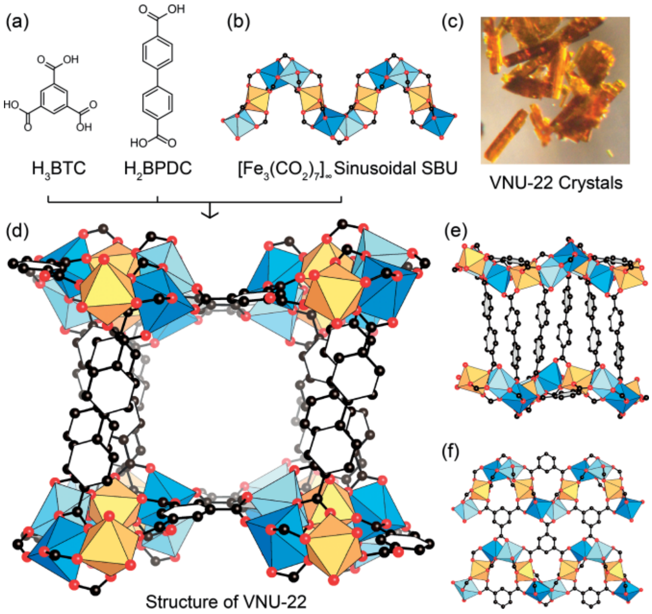
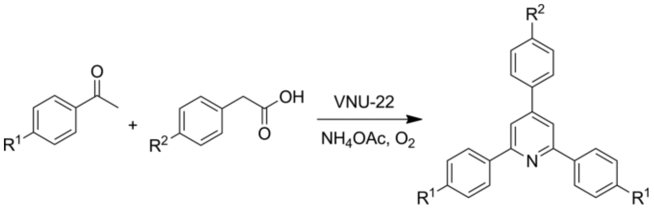


Figure 1. The 3D architecture of VNU-22 is built from sinusoidal rod $[Fe_3(CO_2)_7]_\infty$ clusters (b) that are joined by $BPDC^{2-}$ and BTC^{3-} linkers (a, e and f) to form the rhombic crystals (c) with structure highlighted by a rectangular window of 8.0 × 8.6 Å^2 (d). Atom colors: Fe, blue, light blue and orange polyhedra; C, black; O, red. All H atoms are omitted for clarity.

Additionally, the phase purity of VNU-22 was confirmed by PXRD analysis with the coincidence between the as-synthesized and simulated samples (Figure S1). Subsequently, VNU-22 was activated via CO_2 super critical protocol. Following this, the atomistic connectivity and the structural maintenance after activation were confirmed by PXRD (Figure S1) and Fourier transform-infrared (FT-IR) analysis, which evidenced as the existence of the bands centering at 1612 cm^{-1} ($\nu_{C=O}$ stretch of coordinated carboxylate) (Figure S2). The elemental microanalysis (EA) further confirmed the chemical formula of VNU-22 as $[Fe_3(BTC)(BPDC)_2]\cdot 11.97H_2O$ (Cal: %C= 41.48; %H = 4.01; %N = 0; found %C = 41.48 %H = 3.54; %N = 0.37). The thermal stability and structural robustness of VNU-22 were accessed by thermogravimetric analysis (TGA) and nitrogen adsorption measurement at 77 K. Correspondingly, TGA showed the thermal stability of up to 250 °C with less than 4.0 % weight loss from room temperature, and the Fe_2O_3 residual metal oxides, which is in consistency with those from model structure (Cal: 28.07 %; found 28.26 %) (Figure S3). X-ray photoelectron spectroscopy measurement of VNU-22 indicated the mixed oxidation state of Fe species in the material framework due to the feature peaks in the Fe $2p_{3/2}$ region, namely at 709.5 and 711 eV, attributed to Fe^{II} and Fe^{III} ions, respectively (Figure S4).[14a,16] The structural robustness of VNU-22 was further characterized with BET surface areas of 1029 m^2 g^{-1} (Figure S5), which is in good agreement with the simulated surface areas calculated using Material Studio 7.0 software (1118 m^2 g^{-1}).

Catalytic Studies

The VNU-22 was subsequently used as a heterogeneous catalyst for the synthesis of 2,4,6-triphenylpyridine via cascade reactions between acetophenone and phenylacetic acid with ammonium acetate as a nitrogen source (Scheme 1). Initially, reaction conditions were screened to improve the yield of the desired product (Table 1). The influence of temperature on the yield of heterocyclic product was studied (Entries 1–5, Table 1). The reaction conducted at 120 °C afforded 69 % yield (Entry 4, Table 1). Increasing to 140 °C led to higher yield, however, it was decided to improve the yield by adjusting other factors. One more issue to be considered is the VNU-22 catalyst amount (Entries 6–11, Table 1). Noted that only 10 % yield was detected for the experiment without the VNU-22, thus confirming the need of utilizing the Fe-MOF catalyst (Entry 6, Table 1). Extending the catalyst amount provided higher yield. The solvent displayed a remarkable impact on the transformation (Entries 12–18, Table 1), and chlorobenzene emerged as the best option (Entry 15, Table 1). Having these results, several nitrogen sources were explored for the reaction (Entries 19–23, Table 1), and ammonium acetate exhibited the best performance with 69 % yield being noticed (Entry 23, Table 1). Additionally, the yield was improved to 82 % and 94 % by expanding the amount of ammonium acetate to 3 and 4 equivalents, respectively (Entries 24–25, Table 1).



Scheme 1. Synthesis of triphenylpyridines via cascade reactions utilizing VNU-22 catalyst.

In order to emphasize the superiority of the VNU-22, the reaction was subsequently performed utilizing a series of homogeneous and heterogeneous catalysts (Table 2). First, many iron and copper salts were used as the catalyst for the cascade reactions between acetophenone and phenylacetic acid with ammonium acetate as a nitrogen source under standard conditions. The reaction afforded more than 50 % yields in the presence of $FeCl_2$, $FeCl_3$, and $Fe_2(SO_4)_3$ (Entries 1–3, Table 2), while lower yields were detected for the case of $Fe(NO_3)_3$, $Fe(acac)_3$, and $Fe(OAc)_2$ (Entries 4–6, Table 2). Moreover, it was noted that copper and nickel salts exhibited low activity for the transformation (Entries 7–9, Table 2). Moving to Fe-MOFs, higher yields

Table 1. Screening reaction conditions.[a]

Entry	Temperature (°C)	VNU-22 [mol-%]	Solvent	Nitrogen source (equiv.)	Yield[b]
1	r.t.	5	PhCl	NH_4OAc (1.5)	0
2	80	5	PhCl	NH_4OAc (1.5)	7
3	100	5	PhCl	NH_4OAc (1.5)	11
4	120	5	PhCl	NH_4OAc (1.5)	69
5	140	5	PhCl	NH_4OAc (1.5)	75
6	120	0	PhCl	NH_4OAc (1.5)	10
7	120	0.5	PhCl	NH_4OAc (1.5)	30
8	120	1.5	PhCl	NH_4OAc (1.5)	39
9	120	2.5	PhCl	NH_4OAc (1.5)	63
10	120	3.5	PhCl	NH_4OAc (1.5)	67
11	120	5	PhCl	NH_4OAc (1.5)	69
12	120	5	DMF	NH_4OAc (1.5)	6
13	120	5	DMSO	NH_4OAc (1.5)	13
14	120	5	$MeNO_2$	NH_4OAc (1.5)	5
15	120	5	PhCl	NH_4OAc (1.5)	69
16	120	5	DCB	NH_4OAc (1.5)	5
17	120	5	*n*BuOH	NH_4OAc (1.5)	0
18	120	5	DEG	NH_4OAc (1.5)	0
19	120	5	PhCl	NH_4Cl (1.5)	0
20	120	5	PhCl	NH_4HCO_3 (1.5)	24
21	120	5	PhCl	urea (1.5)	18
22	120	5	PhCl	$(NH_4)_2S_2O_8$ (1.5)	0
23	120	5	PhCl	NH_4OAc (1.5)	69
24	120	5	PhCl	NH_4OAc (3)	82
25	120	5	PhCl	NH_4OAc (4)	94

[a] Reaction conditions: Acetophenone (0.2 mmol); phenylacetic acid (0.3 mmol); solvent (0.5 mL); under oxygen; 12 h; PhCl: chlorobenzene; DMF: *N*,*N'*-dimethylformamide; DMSO: dimethyl sulfoxide; $MeNO_2$: nitromethane; DCB: 1,2-dichlorobenzene; DEG: diethylene glycol. [b] GC yield.

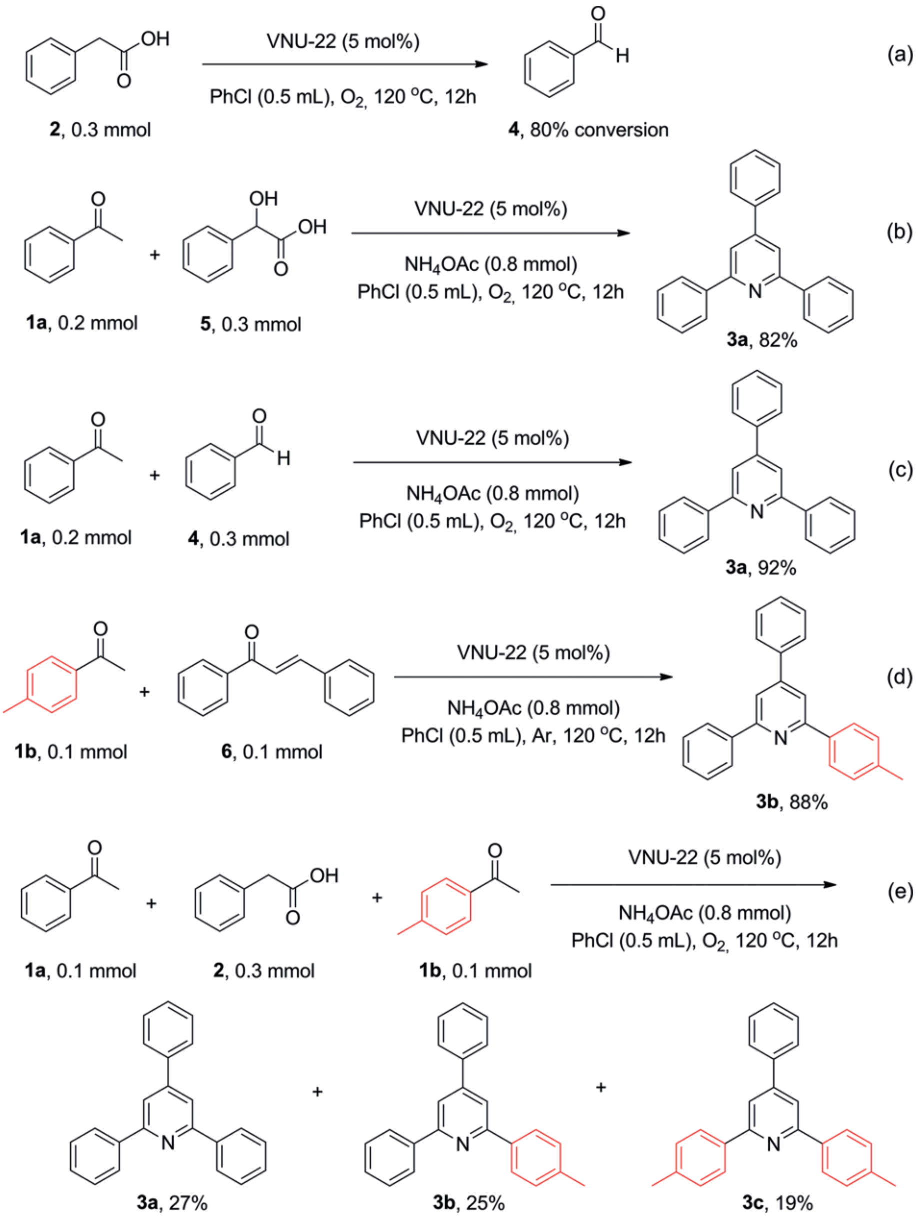
Table 2. The one-pot synthesis of 2,4,6-triphenylpyridine utilizing different catalysts.[a]

Entry	Homogeneous catalyst	Heterogeneous catalyst	Yield[b]
1	$FeCl_3$		51
2	$FeCl_2$		51
3	$Fe_2(SO_4)_3$		51
4	$Fe(NO_3)_3$		48
5	$Fe(acac)_3$		36
6	$Fe(OAc)_2$		48
7	CuI		1
8	$Cu(OAc)_2$		19
9	$Ni(OAc)_2$		7
10		VNU-22	94
11		VNU-20	91
12		$Fe_3O(BDC)_3$	67
13		$Fe_3O(BPDC)_3$	69
14		Cu(BDC)	33
15		$Cu_2(OBA)_2(BPY)$	40
16		Nano $CuFe_2O_4$	11
17		Nano $NiFe_2O_4$	21
18		Nano $CoFe_2O_4$	26
19		Nano Fe_2O_3	13
20		Nano Fe_3O_4	31

[a] Reaction conditions: Acetophenone (0.2 mmol); phenylacetic acid (0.3 mmol); NH_4OAc (0.8 mmol); catalyst (5 mol-%); chlorobenzene (0.5 mL); 120 °C; under oxygen; 12 h. [b] GC yield.

were obtained for the transformation. The reaction utilizing VNU-22 catalyst afforded 94 % yield (Entry 10, Table 2), while 91 % was also recorded for that using VNU-20 catalyst (Entry 11, Table 2). Other Fe-MOFs such as [$Fe_3O(BDC)_3$] and [$Fe_3O(BPDC)_3$] offered lower activity (Entries 12–13, Table 2). Cu-MOFs should not be used for this reaction (Entries 14–15, Table 2). Additionally, several superparamagnetic nanoparticles were tested for the reaction, and low yields of the desired product were observed (Entries 16–20, Table 2). The fact that the VNU-22 was more active than many homogeneous and heterogeneous catalysts highlighted the significant aspects of this iron-organic framework.

To gain more information for the reaction mechanism, several control experiments were conducted (Scheme 2). (i) The reaction did not proceed under an argon atmosphere with no evidence of product being detected, verifying that that oxygen was crucial for this transformation. (ii) The reaction did not occur in the presence of ascorbic acid as antioxidant. (iii) The reaction of phenylacetic acid (**2**) without acetophenone (**1a**) was conducted under standard conditions, and 80 % conversion to benzaldehyde (**4**) was recorded (Scheme 2a). (iv) The reaction between (**1a**) and 2-hydroxy-2-phenylacetic acid (**5**) carried out under standard conditions produced the desired product (**3a**) in 82 % yield (Scheme 2b). Noted that **3a** was detected in trace quantity if the experiment was conducted under argon. (v) The reaction between (**1a**) and (**4**) proceeded to 92 % yield of **3a** under standard conditions (Scheme 2c). Noted that the reaction between (**1a**) and (**4**) carried out under argon offered 94 % yield of **3a**. (vi) The reaction between 4-methylacetophenone (**1b**) and chalcone (**6**) afforded **3a** in 88 % yield (Scheme 2d). Noted that this reaction afforded 10 % yield in the absence of the Fe-MOF. (vii) The reaction between (**1a**), (**1b**), and (**2**) produced 3 products (**3a**, **3b**, and **3c**) in similar yields under stan-

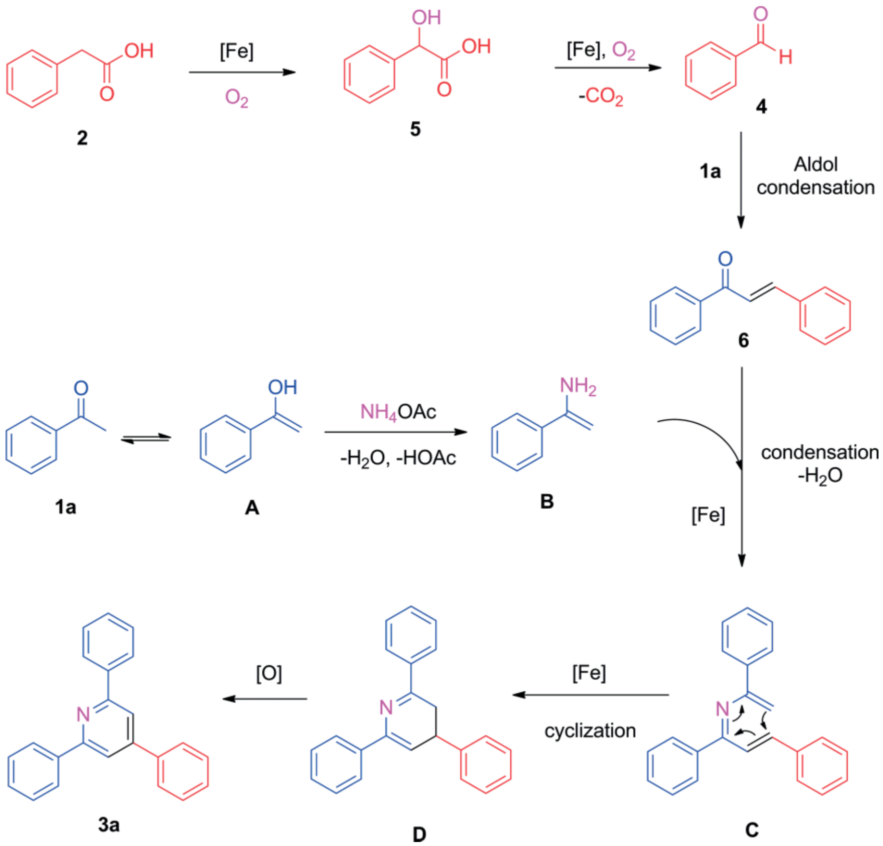


Scheme 2. Control experiments.

dard conditions (Scheme 2e). These results suggested that (**4**), (**5**), and (**6**) could be intermediate products in the catalytic cycle.

On the basis of these observations and the literature, a plausible reaction pathway was proposed (Scheme 3). Initially, the iron-catalyzed aerobic oxidation of phenylacetic acid (**2**) to benzaldehyde (**4**) proceeded via the formation of 2-hydroxy-2-phenylacetic acid (**5**). Indeed, this transformation was well known in the literature.[17] The standard aldol condensation between acetophenone (**1a**) and (**4**) then occurred to form the corresponding chalcone (**6**). Simultaneously, (**1a**) was isomerized to 1-phenylethen-1-ol (**A**), and the reaction of (**A**) with ammonium acetate led to the formation of 1-phenylethen-1-amine (**B**) with water and acetic acid being released.[3,4] Subsequently, the condensation between (**B**) and (**6**) proceeded to generate (1E,2E)-1,3-diphenyl-*N*-(1-phenylvinyl)prop-2-en-1-imine (**C**), following by the cyclization to produce 2,4,6-triphenyl-3,4-dihydropyridine (**D**). Finally, the aerobic oxidation occurred to form the desired product (**3a**). Certainly, Zhang et al. previously demonstrated the generation of **3a** from (**B**) and (**6**) in a HOTf-catalyzed one-pot synthesis of pyridine derivatives from acetophenones and benzylamines.[4]

As the synthesis of 2,4,6-triphenylpyridine from acetophenone and phenylacetic acid with ammonium acetate as a nitrogen source utilizing the VNU-22 catalyst was performed in chlorobenzene phase, the leaching of iron species during the experiment must be investigated. Control experiments were subsequently conducted to clarify if the VNU-22 was a truly heterogeneous catalyst for the transformation or not. The reaction was performed in chlorobenzene at 120 °C for 12 h under an oxygen atmosphere, with 1.5 equivalents of phenylacetic acid and 4 equivalents of ammonium acetate, in the presence



Scheme 3. Plausible reaction pathway.

of 5 mol-% VNU-22 catalyst. Upon completion of the first run, the VNU-22 catalyst was removed from the mixture. The reaction solution was subsequently transferred to a new reactor, and fresh reactants were then added to the mixture. The reactor was consequently heated at 120 °C for 12 h under an oxygen atmosphere. Under these conditions, 14 % yield of the heterocyclic product was detected. It should be noted that the reaction progressed to 10 % yield in the absence of the catalyst (Leaching test 1, Figure 2). In a second experiment, after the first catalytic run, the VNU-22 catalyst was separated, fresh reagents and 10 mol-% $Fe(OAc)_2$ catalyst were added, and the reaction was allowed to proceed at 120 °C for 12 h under an oxygen atmosphere. The presence of $Fe(OAc)_2$ catalyst afforded 56 % yield of the desired product (Leaching test 2, Figure 2). These data suggested that the VNU-22 was a truly heterogeneous catalyst for the synthesis of 2,4,6-triphenylpyridine.

As mentioned earlier, the VNU-22 was more catalytically active many homogeneous and heterogeneous catalysts in the synthesis of 2,4,6-triphenylpyridine from acetophenone and phenylacetic acid with ammonium acetate as a nitrogen source. To furthermore emphasize its significance, the catalyst recovery and reutilization was then explored. The reaction was conducted in chlorobenzene at 120 °C for 12 h under an oxygen atmosphere, with 1.5 equivalents of phenylacetic acid and

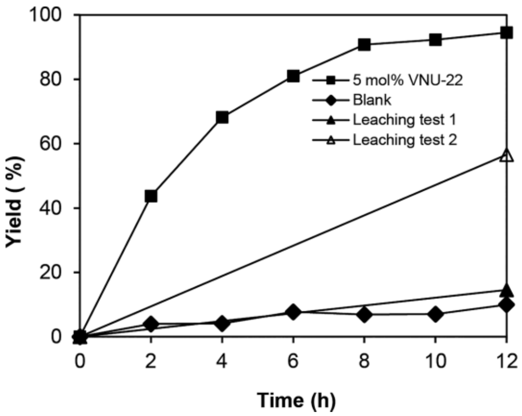


Figure 2. Leaching experiment.

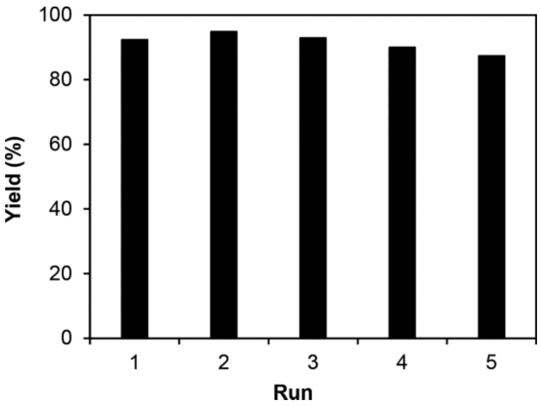


Figure 3. Catalyst reutilization studies.

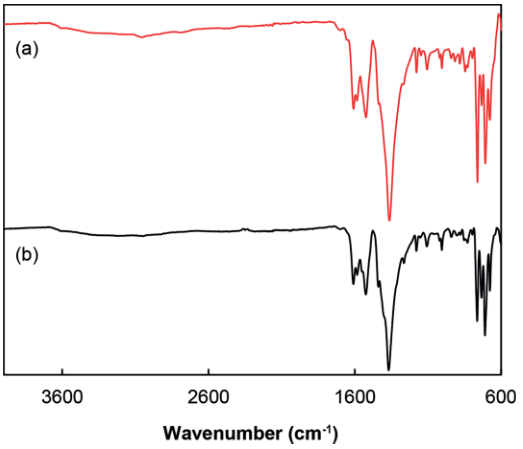


Figure 4. FT-IR spectra of the fresh (a) and recovered (b) VNU-22 catalyst.

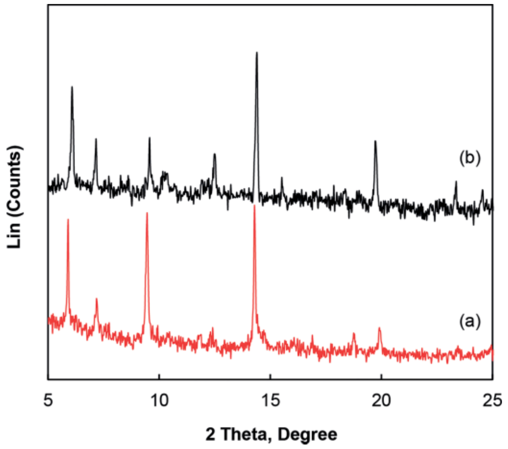
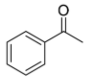
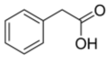
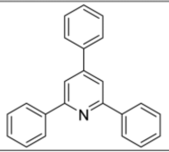
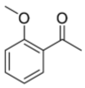
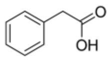
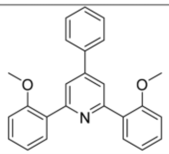
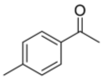
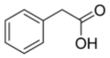
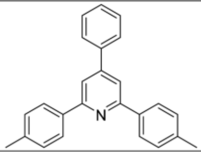
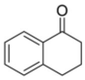
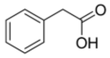
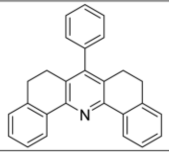
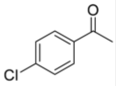
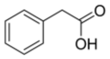
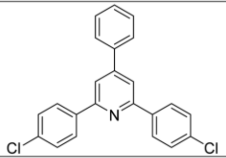
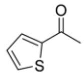
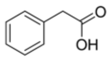
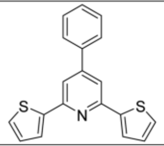
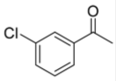
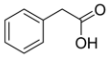
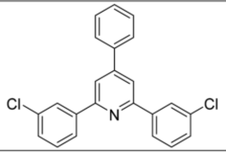
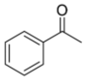
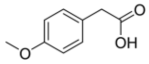
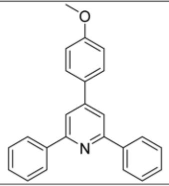
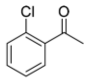
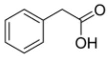
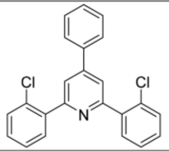
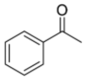
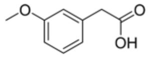
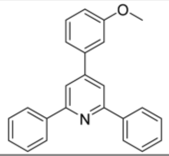
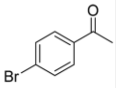
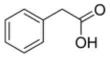
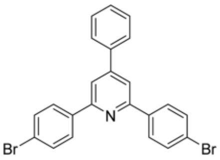
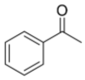
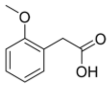
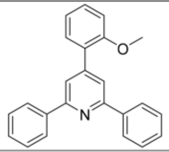
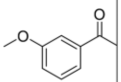
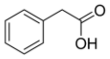
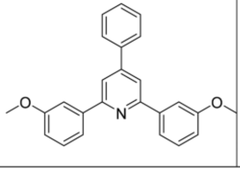
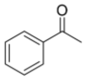
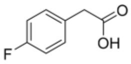
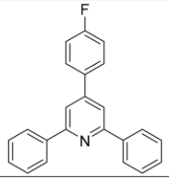


Figure 5. XRD results of the fresh (a) and recovered (b) VNU-22 catalyst.

Table 3. The synthesis of 2,4,6-triphenylpyridines utilizing the VNU-22 catalyst.[a]

Entry	Reactant 1	Reactant 2	Product	Yield[b] (%)	Entry	Reactant 1	Reactant 2	Product	Yield[b] (%)
1				90	8				85
2				89	9				82
3				88	10				87
4				86	11				92
5				72	12				89
6				87	13				77
7				91	14				65

[a] Reaction conditions: Acetophenone (0.2 mmol); phenylacetic acid (0.3 mmol); NH_4OAc (0.8 mmol); VNU-22 catalyst (5 mol-%); chlorobenzene (0.5 mL); 120 °C; under oxygen; 12 h. [b] Isolated yield.

4 equivalents of ammonium acetate, in the presence of 5 mol-% VNU-22 catalyst. Upon completion of the first run, the catalyst was collected using centrifugation, washed thoroughly with anhydrous DMF and chlorobenzene, and evacuated under vacuum at room temperature for 5 h on a Shlenk line. Further catalytic run was subsequently performed utilizing the recovered VNU-22 under the same conditions. It was noted that the VNU-22 catalyst was reutilized several times for the synthesis of 2,4,6-triphenylpyridine without an appreciable deterioration in its performance. Certainly, 87 % yield of 2,4,6-triphenylpyridine was recorded for the transformation in the 5th catalytic run under standard conditions (Figure 3). Moreover, the recovered framework catalyst was characterized by XRD and FT-IR. The FT-IR spectra of the recovered VNU-22 were similar to those of the fresh one (Figure 4). Similarly, XRD results of both reutilized and fresh catalysts revealed that the framework structure was maintained, although a slight difference was noticed (Figure 5).

The work scope was expanded to the synthesis of 2,4,6-triphenylpyridines utilizing the VNU-22 catalyst (Table 3). The reaction was performed in chlorobenzene at 120 °C for 12 h under an oxygen atmosphere, with 1.5 equivalents of phenylacetic acid and 4 equivalents of ammonium acetate, in the presence of 5 mol-% VNU-22 catalyst. The expected products were then isolated by column chromatography. In the first series, acetophenones containing a substituent on benzene ring were utilized for the reaction. Following this protocol, 2,4,6-triphenylpyridine was obtained in 90 % yield (Entry 1, Table 3). 4-Methylacetophenone was reactive, affording 4-phenyl-2,6-di-*p*-tolylpyridine in 89 % yield (Entry 2, Table 3). Moving to haloacetophenone, 2,6-bis(4-chlorophenyl)-4-phenylpyridine (Entry 3, Table 3), and 2,6-bis(3-chlorophenyl)-4-phenylpyridine (Entry 4, Table 3) were generated in 88 % and 86 % yields, respectively. 2-Chloroacetophenone proceeded more difficultly, though 2,6-bis(2-chlorophenyl)-4-phenylpyridine (Entry 5, Table 3) was obtained in 72 % yield. Similarly, 2,6-bis(4-bromophenyl)-4-phenylpyridine (Entry 6, Table 3) was produced in 87 % yield for the case of 4-bromoacetophenone. In the same way, 2,6-bis(3-methoxyphenyl)-4-phenylpyridine (Entry 7, Table 3), and 2,6-bis(2-methoxyphenyl)-4-phenylpyridine (Entry 8, Table 3) were formed in 91 % and 85 % yields, respectively. 3,4-Dihydronaphthalen-1(2*H*)-one was also reactive, producing 7-phenyl-5,6,8,9-tetrahydrodibenzo[c,h]acridine (Entry 9, Table 3) in 82 % yield. Interestingly, 4-phenyl-2,6-di(thiophen-2-yl)pyridine (Entry 10, Table 3) was achieved in 87 % yield. In the second series, phenylacetic acids containing a substituent on benzene ring were used, and corresponding products were obtained in high yields (Entries 11–14, Table 3).

Conclusions

A new iron-organic framework, VNU-22 $[Fe_3(BTC)(BPDC)_2]\cdot 11.97H_2O$, consisted of mixed-linkers of BTC^{3-}, $BPDC^{2-}$ and infinite $[Fe_3(CO_2)_7]_\infty$ rod SBU, was synthesized and characterized by a variety of techniques. The VNU-22 was subsequently utilized as a recyclable heterogeneous catalyst in the synthesis of 2,4,6-triphenylpyridines from acetophenones and phenylacetic acids with ammonium acetate as a nitrogen source under an oxygen atmosphere. Triphenylpyridines were generated via cascade reactions, including decarboxylation of phenylacetic acids via iron-catalyzed oxidative Csp^3–H bond activation, condensation, cyclization, and oxidation. The transformation was dramatically adjusted by the solvent, in which chlorobenzene emerged as the best option. The VNU-22 was more active in the synthesis of 2,4,6-triphenylpyridines than many homogeneous and heterogeneous catalysts. The framework catalyst was recovered and reutilized without an appreciable deterioration in its performance. The significance that 2,4,6-triphenylpyridines were achieved via cascade reactions using a recyclable catalyst should attract interests from the chemical industry.

Experimental Section

Preparation of the Fe-MOF VNU-22: H_3BTC (0.021 g, 0.1 mmol), H_2BPDC (0.12 g, 0.49 mmol), anhydrous $FeCl_2$ (0.09 g, 0.705 mmol), and anthraquinone (0.12 g, 0.57 mmol) were dissolved into DMF (12 mL). The mixture was then sonicated for 5 min to achieve a transparent solution. Following this step, the reaction mixture was distributed into glass tubes, subsequently flamed and sealed under ambient atmosphere. These tubes were stabilized in an oven at 180 °C for 72 h, and reddish rhombic crystals of VNU-22 were formed during the experiment. The product was consequently treated with DMF (5 × 15 mL), and methanol/water (10 % water, 5 × 15 mL), and dry methanol (5 × 15 mL) for solvent exchange. Finally, the solid was exchanged by supercrital CO_2 (four times), and consequently activated under vacuum to afford the corresponding framework (0.064 g, 75 % base on H_3BTC).

Catalytic Studies: To a 12-mL screw-cap vial containing chlorobenzene (0.5 mL) was added acetophenone (24.0 mg, 0.2 mmol), phenylacetic acid (40.8 mg, 0.3 mmol), NH4OAc (60.0 mg, 0.8 mmol), VNU-22 catalyst (5 mol-%), and diphenyl ether (17.2 mg, 0.1 mmol) as an internal standard. The catalyst amount was calculated regarding the iron/acetophenone molar ratio. The reaction tube was back-filled with oxygen and the resulting mixture was subsequently stirred at 120 °C for 12 h. The reaction yield monitored by taking aliquots from the reaction mixture, and quenched with brine. The organic components were consequently extracted into ethyl acetate (2 mL), dried with anhydrous Na_2SO_4, and analyzed by GC with reference to diphenyl ether. To isolate the desired product, after disappearance of the reactant (monitored by TLC), the mixture was slowly cooled to room temperature and diluted with ethyl acetate (20 mL), washed with $NaHCO_3$ solution (5 % in water, 3 × 5 mL), dried with anhydrous Na_2SO_4, and concentrated under vacuum. The crude product was purified by column chromatography with hexane/ethyl acetate solvent system. The product structure was confirmed by GC–MS, ^1H NMR, and ^{13}C NMR.

CCDC 1837779 (for VNU-22) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

Acknowledgments

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Keywords: Pyridines · Metal-organic frameworks · Heterocycles · Cascade reactions · Cyclization

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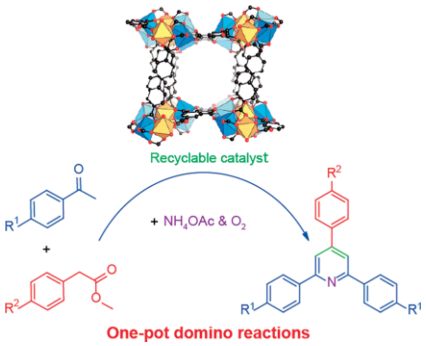
Triphenylpyridine Linkers

S. H. Doan, N. K. Q. Tran, P. H. Pham, V. H. H. Nguyen, N. N. Nguyen, P. T. M. Ha, S. Li, H. V. Le, N. T. H. Le, T. N. Tu, N. T. S. Phan** 1–9

A New Synthetic Pathway to Triphenylpyridines via Cascade Reactions Utilizing a New Iron-Organic Framework as a Recyclable Heterogeneous Catalyst



Iron-based Metal-organic framework (VNU-22) was utilized as a recyclable heterogeneous catalyst in the synthesis of 2,4,6-triphenylpyridines via cascade reactions.

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