Ammonium metavanadate (NH₄VO₃): a highly efficient and eco-friendly catalyst for one-pot synthesis of pyridines and 1,4-dihydropyridines

Jamal Rahimi¹, Maryam Niksefat¹, Marzieh Heidari², Mehdi Naderi¹, Hadis Abbasi¹, Mohammad Tajik Ijdani¹ & Ali Maleki¹,
*email: maleki@iust.ac.ir

In this study, we reported the ammonium metavanadate (NH₄VO₃) as an efficient, cost-effective, and mild catalyst for the synthesis of substituted pyridines via a one-pot pseudo four-component reaction. Furthermore, we investigated Hantzsch 1,4-dihydropyridines (1,4-DHPs) synthesis and oxidation of 1,4-DHPs to their corresponding pyridines. The present approach offers a rapid methodology for accessing various pyridines with broad functional group tolerance and good yields using NH₄VO₃ catalyst as a green catalyst.

For several decades nitrogen-containing six-membered heterocyclic compounds have attracted the interest of synthetic organic chemists due to their pharmaceutical and biological properties. Among the nitrogen heterocycles, pyridine derivatives are well known as calcium channel blockers and exhibit therapeutic effects, such as vasodilator, bronchodilator, geroprotective, hepatoprotective, neuroprotective, and anti-tumor activity. For example, there are many pharmaceutical pyridine compounds (Fig. 1) such as (A) and (B), as selective modulators of human adenosine receptors implicated in asthma, Parkinson’s disease, epilepsy, kidney disease, and cancer, as well as cerivastatin (C) for the treatment of atherosclerosis and other coronary diseases. Pyridine derivatives are not only privileged scaffolds for drug discovery but also used as building blocks reagents in organic synthesis and ligands in coordination chemistry. Due to their importance, the development of novel synthetic methods for the preparation of pyridine derivatives is of interest.

The traditional so-called Hantzsch synthesis of 1,4-DHPs includes one-pot cyclocondensation of a β-ketoester with an aldehyde and a nitrogen source, which occurs either in acetic acid at room temperature or by refluxing in alcohols; this protocol has some drawbacks such as prolonged reaction times and low yields. Therefore, numerous modifications have been made to the original Hantzsch reaction, such as using microwave radiation, ionic liquid, SiO₂/NaHSO₄, metal triflates, I₂, ceric ammonium nitrate (CAN) and ZnO.

Recently, the oxidation of 1,4-DHPs was successfully carried out by using various oxidants, such as peroxysulfate-Co(II), silica-modified sulfuric acid/NaNO₂, Co-naphthenate, KBrO₃/SnCl₄.5H₂O, MnO₂, silica chromate, urea- hydrogen peroxide catalyzed by molecular iodine, b-cyclodextrin, silica-sulfuric acid and Al(NO₃)₃.9H₂O or Fe(NO₃)₃.9H₂O.

In recent years, the application of the bifunctional solid acid/noble metal Pd/C/K-10 catalyst was reported for the one-pot synthesis of pyridine derivatives. In addition, Khaskel and Barman reported the one-pot synthesis of pyridines in ethanol by benzyltrimethylammoniumfluoride hydrate (BTMAFH) and K₂S₂O₈. Ghosh et al. reported the direct synthesis of pyridine derivatives using visible light in aqueous media catalyzed by non-ionic surfactant Triton-X-100. Although, many of the reported methods for synthesis of pyridine derivatives offer distinct benefits, some of them still have some drawbacks, such as long reaction times, expensive reagents, harsh conditions, low product yields, tedious work-up, and by-products formation.

Hence, the development of a new procedure for the one-pot synthesis of pyridine derivatives would be highly desirable. Recently, NH₄VO₃ has been utilized as an inorganic acid and economical catalyst in organic reactions.
Furthermore, to the best of our knowledge the use of NH$_4$VO$_3$ in the synthesis of pyridine derivatives has been never reported before. In continuation of our previous works on the introduction of new catalysts in organic synthesis$^{37-43}$, herein, we report the use of NH$_4$VO$_3$ without any post-modification as an efficient, inexpensive, and eco-friendly catalyst for the synthesis of substituted pyridines via one-pot pseudo four-component reaction, including a combination of the Hantzsch synthesis and the subsequent oxidation step for the first time (Fig. 2).

**Experimental**

**General.** All solvents, chemicals, and reagents were purchased from Merck, Fluka, and Sigma-Aldrich chemical companies. Melting points were measured with an Electrothermal 9100 apparatus and are uncorrected. FT-IR spectra were obtained over 400–4000 cm$^{-1}$ with a Shimadzu IR-470 spectrometer using KBr pellets. $^1$H-NMR and $^{13}$C-NMR spectra were recorded by a Bruker Avance DRX 500 spectrometer. All the synthesized products were known, and the structure of the isolated products was confirmed by previously reported data.

**General procedure for one-pot synthesis of pyridines.** A mixture of an aldehyde 1 (1.0 mmol), ammonium acetate 2 (2.0 mmol), ethyl acetooacetate 3 (2.0 mmol), and ammonium metavanadate (NH$_4$VO$_3$) (117.0 mg) in 3.0 mL acetic acid was stirred under reflux condition for the appropriate time (Table 7). After completion of the reaction, as indicated by thin-layer chromatography (TLC), the catalyst (NH$_4$VO$_3$) was
separated by filtration. Then, products afforded by evaporation of the solvent, and recrystallized from diethyl ether to give the pure desired pyridines (5).

General procedure for preparation of 1,4-DHPs. A mixture of an aldehyde 1 (1.0 mmol), ammonium acetate 2 (2.0 mmol), ethyl acetoacetate 3 (2.0 mmol), and ammonium metavanadate (NH₄VO₃) (15.0 mg) in 3.0 mL ethanol was stirred under reflux condition, as indicated by thin-layer chromatography (TLC), the catalyst (NH₄VO₃) was separated by filtration, washed with ethanol, and reused five times in other fresh reactions without a considerable loss of activity. Then, products (4) are afforded by evaporation of the solvent, followed by recrystallization from ethanol.

General procedure for oxidative aromatization of 1,4-DHPs. To a solution of 1,4-DHPs 4 (1.0 mmol) in 3.0 mL of acetic acid, ammonium metavanadate (NH₄VO₃) (117.0 mg) was added. The resulting mixture was refluxed for an appropriate time (Table 5). After completion of the reaction (monitored by TLC), the mixture was cooled to room temperature and the catalyst was filtered off. Then the filtrate was evaporated and recrystallized from diethyl ether to give the pure desired pyridines (5).

Spectral data. Diethyl 4-(4-methoxyphenyl)-2,6-dimethyl-3,5-pyridinedicarboxylate (5d): FT-IR (KBr; υ/cm⁻¹): 2985, 2929, 1724, 1558, 1510, 1488, 1294, 1232, 1107, 1045, 860, 792; ¹H NMR (500 MHz, CDCl₃): δH (ppm) = 8.94 (s, 1H, NH), 7.47 (d, 2H, J = 8.4 Hz, H-Ar), 7.17 (d, 2H, J = 8.4 Hz, H-Ar), 6.90–6.97 (m, 2H), 5.97 (s, 1H, NH), 4.01–4.11 (m, 4H, CH₂), 2.33 (s, 6H, CH₃), 2.45 (s, 6H, CH₃), 1.38 (t, 6H, J = 7.1 Hz, CH₂), 0.97 (t, 6H, J = 7.1 Hz, CH₂).

Diethyl 4-(4-chloro-phenyl)-2,6-dimethyl-3,5-pyridinedicarboxylate (5f): FT-IR (KBr; υ/cm⁻¹): 2790, 2127, 1371, 1271, 1177, 1488, 1652, 1693, 2989, 3345, 3378; ¹H NMR (500 MHz, DMSO): δH (ppm) = 8.94 (s, 1H, NH), 7.17–7.23 (m, 3H, H-Ar), 6.01 (s, 1H, NH), 5.04 (s, 1H, CH₂), 4.16–4.24 (m, 4H, CH₂), 2.59 (s, 6H, CH₃), 1.85 (s, 3H, OCH₃), 1.33 (t, 6H, J = 7.1 Hz, CH₂), 0.90 (t, 6H, J = 7.1 Hz, CH₂).

Results and discussion

Regarding the fact that the one-pot approach to the synthesis of substituted pyridines through Hantzsch synthesis is hardly carried out and there are only a few literatures reported in this field. Hence, the efficiency of ammonium metavanadate (NH₄VO₃) was investigated in the one-pot synthesis of pyridine derivatives. In an initial attempt, the condensation of 4-chlorobenzaldehyde (1.0 mmol) with ethyl acetoacetate (2.0 mmol) and ammonium acetate (2.0 mmol) as a model reaction (Fig. 3) was examined in the presence of different catalytic amounts of NH₄VO₃ (Table 2). After completion of the reaction, as indicated by thin-layer chromatography (TLC), the catalyst (NH₄VO₃) was separated by filtration, washed with ethanol, and reused five times in other fresh reactions without a considerable loss of activity. Then, products (4) are afforded by evaporation of the solvent, followed by recrystallization from ethanol.

To optimize the amount of catalyst and reaction conditions for the one-pot synthesis of pyridines, the model reaction was examined in acetic acid (Table 1). As shown in Table 1, the best results were achieved when the reaction was carried out in the presence of 117.0 mg of NH₄VO₃ as the catalyst in acetic acid under reflux conditions (entry 1, Table 1). Increasing the amount of catalyst (117.0–120.0 mg) did not improve the yield of the desired product (entries 1–5, Table 1). In the absence of NH₄VO₃ catalyst, the reaction was not successful (entry 11, Table 1).
After optimizing the reaction conditions, to explore the scope of the reaction, a series of pyridine derivatives were synthesized by various aldehydes including both electron-donating and electron-withdrawing substituents (Table 7). All the aldehydes with both electron-withdrawing groups and electron-donating groups reacted very well, giving high yields of the desired products in short reaction times. Based on the results, we propose a plausible mechanism for the one-pot synthesis of pyridines (Fig. 4). This mechanistic pathway includes a combination of the Hantzsch synthesis and the subsequent oxidation step. First, the ammonium (NH$_4^+$) group in the structure of NH$_4$VO$_3$ activates the carbonyl functional groups of aldehyde and ethyl acetoacetate by hydrogen bonding. Therefore, it increases the carbonyl activity to Knoevenagel condensation with enol form of ethyl acetoacetate to give the corresponding Knoevenagel intermediate (I). In the next step, the reaction of the second molecule of ethyl acetoacetate with ammonium acetate gives the imine intermediate (II). The Michael addition of I with enamine form of II occurs to form intermediate III, which is activated through hydrogen bonding from NH$_4$VO$_3$ to facilitate cyclization and elimination of water, affording the desired 1,4-DHP derivatives. In continue, acetic acid using NH$_4$VO$_3$ as a catalyst is converted into acetate ion which is leading to an acid–base reaction with 1,4-DHPs. In the following, the negative charge of nitrogen of intermediate (IV) binds with the vacant “d” orbital of transition metal vanadium to achieve the stable oxidation state of vanadium. The last step might be progressed through unusual hydride transfer and H$_2$ releasing from (V). For proving this opinion, the reaction was evaluated under a nitrogen atmosphere (entry 2, Table 1). The results show that the oxidation reaction progressed in an atmosphere of nitrogen similar to the air or oxygen atmosphere condition (entries 1–3, Table 1). Due to electron-donating from the nitrogen lone pairs into the anti-bonding orbital of C–H ($s^*_{C-H}$ orbital), the C–H bond is easily broken by reaction with a proton to afford molecular hydrogen. This phenomenon has been known as the anomeric effect.

Although there are a few literatures that reported on the direct approach for the one-pot synthesis of pyridines, this method is superior to the earlier methods in terms of yields, reaction time, and mild reaction conditions (Table 2).

To further confirm the possible mechanism, we also examined the efficiency of NH$_4$VO$_3$ as a catalyst for the one-pot synthesis of 1,4-DHPs. To optimize the reaction conditions. The condensation of 4-chlorobenaldehyde (1.0 mmol) with ethyl acetoacetate (2.0 mmol), ammonium acetate (2.0 mmol), AcOH (3.0 mL), under air condition. "Isolated yields." Under N$_2$ atmosphere. "Under O$_2$ atmosphere.

Table 1. Screening of the amount of catalyst and reaction conditions for the one-pot synthesis of pyridines. Reaction conditions: 4-chlorobenaldehyde (1.0 mmol), ethyl acetoacetate (2.0 mmol), ammonium acetate (2.0 mmol), AcOH (3.0 mL), under air condition. "Isolated yields." Under N$_2$ atmosphere. "Under O$_2$ atmosphere.

| Entry | Solvent   | Time(min) | Amount of catalyst (mg) | Temperature (°C) | Yielda (%) |
|-------|-----------|-----------|-------------------------|------------------|------------|
| 1     | Acetic acid | 10        | 117                     | Reflux           | 96         |
| 2     | Acetic acid | 10        | 117                     | Reflux           | 96$^a$     |
| 3     | Acetic acid | 10        | 117                     | Reflux           | 96$^b$     |
| 4     | Acetic acid | 10        | 120                     | Reflux           | 96         |
| 5     | Acetic acid | 10        | 180                     | Reflux           | 96         |
| 6     | Acetic acid | 60        | 29                      | Reflux           | 67         |
| 7     | Acetic acid | 60        | 58                      | Reflux           | 73         |
| 8     | Acetic acid | 60        | 88                      | Reflux           | 85         |
| 9     | Acetic acid | 60        | 116                     | Reflux           | 90         |
| 10    | Acetic acid | 60        | 117                     | r.t              | 65         |
| 11    | Acetic acid | 60        | –                       | Reflux           | 0$^c$      |
In the absence of NH$_4$VO$_3$ as the catalyst, the reaction proceeded slowly with a low yield (entry 16, Table 3). As seen in Table 3 (entries 7–12) using 15.0–23.0 mg of the catalyst (NH$_4$VO$_3$) showed higher activity for the synthesis of 1,4-DHPs. However, when the amount of catalyst increased to 18.0–23.0 mg (entries 10–12, Table 3) the yield of the desired product (93%) did not improve. Among the investigated solvents, ethanol is the best choice with its short reaction time, high yield, cheapness, and being environmentally friendly for this reaction.

According to the results in Tables (1,3), it is obvious that in the absence of acetic acid and using other solvents the
1,4-DHPs form as the desired products. After optimizing the reaction conditions, the effect of substitution on the aldehydes has also been studied. As shown in Table 7 all the aromatic aldehydes with both electron-withdrawing groups and electron-donating groups reacted very well, giving high yields of the desired products. As expected substituted aldehydes with electron-withdrawing groups require a shorter reaction time in comparison to those with electron-donating groups.

**Figure 5.** Hantzsch synthesis of 1,4-DHPs catalyzed by NH₄VO₃.

**Table 3.** Optimization of the NH₄VO₃ catalyzed model reaction for the synthesis of Hantzsch 1,4-DHPs.

| Entry | Solvent                | Time(min) | Amount of catalyst (mg) | Temperature (°C) | Yielda (%) |
|-------|------------------------|-----------|-------------------------|------------------|------------|
| 1     | Dimethyl sulfoxide     | 20        | 15                      | Reflux           | 75         |
| 2     | Polyethylene glycol    | 45        | 15                      | Reflux           | 90         |
| 3     | Dimethylformamide      | 20        | 15                      | Reflux           | 45         |
| 4     | Tetrahydrofuran        | 45        | 15                      | Reflux           | 37         |
| 5     | Acetonitrile           | 20        | 15                      | Reflux           | 85         |
| 6     | Water                  | 20        | 15                      | Reflux           | 55         |
| 7     | Ethanol                | 20        | 15                      | Reflux           | 93         |
| 8     | Ethanol                | 45        | 15                      | Reflux           | 93         |
| 9     | Ethanol                | 45        | 15                      | r.t              | 65         |
| 10    | Ethanol                | 20        | 18                      | Reflux           | 93         |
| 11    | Ethanol                | 20        | 21                      | Reflux           | 93         |
| 12    | Ethanol                | 20        | 23                      | Reflux           | 93         |
| 13    | Ethanol                | 20        | 14                      | Reflux           | 85         |
| 14    | Ethanol                | 45        | 13                      | Reflux           | 70         |
| 15    | Ethanol                | 45        | 12                      | Reflux           | 58         |
| 16    | Ethanol                | 45        | –                       | Reflux           | 31         |

**Table 4.** Comparison of the efficiency of NH₄VO₃ with other catalysts for synthesizing 1,4-DHP (1f).

| Entry | Catalyst (amount of catalyst) | Condition                  | Time (min) | Yielda (%) | References |
|-------|-------------------------------|----------------------------|------------|------------|------------|
| 1     | Nano-ZnO (10 mol%)            | EtOH/r.t                   | 50         | 83         | 46         |
| 2     | Nano-g-Alumina (10 mg)        | EtOH/r.t                   | 50         | 85         | 44         |
| 3     | Nano-ZMS-5 (10 mg)            | EtOH/r.t                   | 55         | 90         | 44         |
| 4     | Succinic acid (0.5 mmol)      | EtOH: H₂O/80 (°C)          | 150        | 92         | 47         |
| 5     | PPh₃ (20 mol%)                | EtOH/reflux                | 5 h        | 82         | 49         |
| 6     | PPh₃ (20 mol%)                | EtOH/reflux                | 120        | 81         | 49         |
| 7     | NH₄VO₃ (15 mg)                | EtOH/reflux                | 20         | 93         |            |

*a* Isolated yields.
Moreover, the catalytic activity of the NH₄VO₃ for the synthesis of 1,4-DHPs was compared to the other reported catalysts in Table 4.

We also extended our study to the oxidation of the synthesized 1,4-DHPs. Compound 4f (diethyl 4-(4-chlorophenyl)-2,6-dimethyl-1,4-dihydropyridine-3,5-dicarboxylate) was used as a model substrate to optimize the oxidation reaction conditions (Fig. 6).

As revealed in Table 5 (entries 1–8), the nature of the solvent is an important factor in the oxidation of 1,4-DHPs to the corresponding pyridines. The effect of the solvent in the oxidation reaction, in dichloromethane, ethanol, chloroform, H₂O, acetonitrile, formic acid, and tetrahydrofuran was investigated; no oxidation occurred in these solvents. While by addition of acetic acid as the solvent to the reaction mixture, the yield of the desired product reached 96% under reflux conditions (entry 8, Table 5), this observation suggests that acetic acid is

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**Table 5.** Optimization of reaction conditions in the oxidation of 1,4-DHPs. Reaction conditions: 1,4-DHPs (1.0 mmol), solvent (3.0 mL). aIsolated yields. bUnder N₂ atmosphere. cUnder O₂ atmosphere.

| Entry | Solvent         | Time (min) | Amount of catalyst (mg) | Temperature | Yield (%) |
|-------|-----------------|------------|-------------------------|-------------|-----------|
| 1     | Dichloromethane | 1080       | 117                     | Reflux      | 0         |
| 2     | Chloroform      | 1080       | 117                     | Reflux      | 0         |
| 3     | Ethanol         | 1080       | 117                     | Reflux      | 0         |
| 4     | Water           | 1080       | 117                     | Reflux      | 0         |
| 5     | Acetonitrile    | 1080       | 117                     | Reflux      | 0         |
| 6     | Formic acid     | 1080       | 117                     | Reflux      | 0         |
| 7     | Tetrahydrofuran | 1080       | 117                     | Reflux      | 0         |
| 8     | Acetic acid     | 10         | 117                     | Reflux      | 96        |
| 9     | Acetic acid     | 120        | 117                     | r. t        | 85        |
| 10    | Acetic acid     | 10         | 117                     | Reflux      | 96        |
| 11    | Acetic acid     | 60         | 58                      | Reflux      | 73        |
| 12    | Acetic acid     | 60         | 88                      | Reflux      | 85        |
| 13    | Acetic acid     | 60         | 116                     | Reflux      | 90        |
| 14    | Acetic acid     | 10         | 120                     | Reflux      | 96        |
| 15    | Acetic acid     | 10         | 180                     | Reflux      | 96        |
essential for the oxidation reaction. Additionally, the model substrate converts into the corresponding pyridine in acetic acid at room temperature (entry 9, Table 5). The model substrate was treated with 58.0–180.0 mg of NH₄VO₃ in the presence of acetic acid under reflux conditions (entries 10–16, Table 5). The satisfactory yield of the desired product can be obtained with 117.0 mg of NH₄VO₃ (entry 8, Table 5). The experiment was conducted in the oxygen, nitrogen, and air atmosphere (entries 8–11, Table 5), the oxidation reaction progressed in the nitrogen atmosphere the same as in normal reaction conditions using air or oxygen atmosphere.

Under the optimized reaction conditions, the catalytic performance of NH₄VO₃ was further evaluated for the oxidation reaction of various 1,4-DHPs containing electron-withdrawing and donating substituents (Table 7). The Hantzsch 1,4-DHPs including a variety of substituents were converted to the corresponding pyridines in excellent yield (Table 7). Based on the results for the oxidation of 1,4-DHPs by other catalysts reported previously (Table 6), the NH₄VO₃ can act as a highly efficient heterogeneous catalyst in oxidation reaction through a facile method (Table 7).

![Chemical structure](image)

**Table 6.** Comparison of the results for the oxidation of 1,4-DHP (4f.) using other catalysts. *Isolated yield.

| Entry | Catalyst | Condition | Time | Yield* (%) | References |
|-------|----------|-----------|------|------------|------------|
| 1     | CuBr₂ (3 mmol) | CH₃COOCH₂CH₃/CHCl₃/reflux | 2 h   | 81         | 58         |
| 2     | TBA-eosinY/ K₂CO₃ (1 mol %) | Methanol/water/LED irradiation/Air | 12 h  | 85         | 59         |
| 3     | H₂O₂/V₂O₅ (5 mol %) | CH₃CN/rt | 1 h   | 95         | 60         |
| 4     | PhCH₂Ph₃PSO₅/BiCl₃ (1 eq/3 eq) | CH₃CN/rt | 1/40 h | 81         | 61         |
| 5     | NH₄PF₆/Co(OAc)₂·4H₂O (20 mol %/0.5 mol %) | CH₃CN/Air/reflux | 4 h   | 98         | 62         |
| 6     | NH₄VO₃ (117 mg) | AcOH/reflux | 10 min | 98         | This work |

The Hantzsch 1,4-DHPs including a variety of substituents were converted to the corresponding pyridines in excellent yield (Table 7). Based on the results for the oxidation of 1,4-DHPs by other catalysts reported previously (Table 6), the NH₄VO₃ can act as a highly efficient heterogeneous catalyst in oxidation reaction through a facile method (Table 7).
| Entry | Aldehyde (1) | Product (5) Path A<sup>a</sup> | Product (5) Path B<sup>b</sup> | Mp (°C) ref | Product (4)<sup>c</sup> | Mp (°C) ref |
|-------|-------------|-------------------------------|-------------------------------|------------|----------------|------------|
|       |             | Time (min) | Yield<sup>d</sup> (%) | Time (min) | Yield<sup>d</sup> (%) | Time (min) | Yield<sup>d</sup> (%) | Time (min) | Yield<sup>d</sup> (%) |
| 1     | Formaldehyde | 5           | 99               | 5           | 98               |                   |                   |
|       |             |             |                  |             |                  | 69–70<sup>35</sup> | (4a)          |
|       |             |             |                  |             |                  | 165–168<sup>54</sup> |
| 2     | PhCHO       | 10          | 99               | 15          | 96               |                   |                   |
|       |             |             |                  |             |                  | 59–61<sup>35</sup> | (4b)          |
|       |             |             |                  |             |                  | 151–153<sup>54</sup> |
| 3     | 4-(Me)<sub>C</sub>6H<sub>4</sub>CHO | 10          | 95               | 15          | 97               |                   |                   |
|       |             |             |                  |             |                  | 71–73<sup>29</sup> | (4c)          |
|       |             |             |                  |             |                  | 133–136<sup>54</sup> |
| 4     | 4-(O<sub>Me</sub>)<sub>C</sub>6H<sub>4</sub>CHO | 10          | 100              | 25          | 96               |                   |                   |
|       |             |             |                  |             |                  | 57–58<sup>34</sup> | (4d)          |
|       |             |             |                  |             |                  | 163–165<sup>54</sup> |
| 5     | 4-(Br)<sub>C</sub>6H<sub>4</sub>CHO | 10          | 99               | 10          | 98               |                   |                   |
|       |             |             |                  |             |                  | 51–53<sup>29</sup> | (4e)          |
|       |             |             |                  |             |                  | 160–162<sup>54</sup> |
| 6     | 4-(Cl)<sub>C</sub>6H<sub>4</sub>CHO | 10          | 96               | 10          | 97               |                   |                   |
|       |             |             |                  |             |                  | 71–72<sup>29</sup> | (4f)          |
|       |             |             |                  |             |                  | 144–147<sup>57</sup> |

Continued
| Entry | Aldehyde (1) | Product (5) Path A<sup>+</sup> | Product (5) Path B<sup>+</sup> | Mp (°C) ref. | Product (4)<sup>c</sup> | Mp (°C) ref. |
|-------|-------------|-------------------------------|-------------------------------|-------------|----------------|-------------|
|       |             | Time (min) Yield<sup>d</sup> (%) | Time (min) Yield<sup>d</sup> (%) |             | Time (min) Yield<sup>d</sup> (%) |             |
| 7     | 4-(F)C<sub>6</sub>H<sub>4</sub>CHO | 10 99 | 15 98 | 88–89<sup>20</sup> | 20 90 | 153–156<sup>44</sup> |
|       |             | ![Image](5g)                  | ![Image](4g)                  |             | ![Image](5g)                  | ![Image](4g)                  |
| 8     | 4-(OH)C<sub>6</sub>H<sub>4</sub>CHO | 15 99 | 20 95 | 171–174<sup>46</sup> | 60 85 | 227–230<sup>44</sup> |
|       |             | ![Image](5h)                  | ![Image](4h)                  |             | ![Image](5h)                  | ![Image](4h)                  |
| 9     | 3-(OH)C<sub>6</sub>H<sub>4</sub>CHO | 15 99 | 10 97 | 150–153<sup>30</sup> | 45 88 | 187–189<sup>44</sup> |
|       |             | ![Image](5i)                  | ![Image](4i)                  |             | ![Image](5i)                  | ![Image](4i)                  |
| 10    | 3-(NO<sub>2</sub>)C<sub>6</sub>H<sub>4</sub>CHO | 10 98 | 30 95 | 60–61<sup>33</sup> | 40 91 | 163–166<sup>44</sup> |
|       |             | ![Image](5j)                  | ![Image](4j)                  |             | ![Image](5j)                  | ![Image](4j)                  |
| 11    | 4-(CN)C<sub>6</sub>H<sub>4</sub>CHO | 20 99 | 10 99 | 100–102<sup>20</sup> | 15 96 | 194–196<sup>44</sup> |
|       |             | ![Image](5k)                  | ![Image](4k)                  |             | ![Image](5k)                  | ![Image](4k)                  |
| 12    | Furan-2-car- | 10 80 | 10 98 |  | 16 98 | 161–163<sup>41</sup> |
|       | baldehyde   | ![Image](5l)                  | ![Image](4l)                  |             | ![Image](5l)                  | ![Image](4l)                  |

Continued
Conclusion
In conclusion, a novel and convenient approach for the one-pot synthesis of pyridine derivatives through the one-pot pseudo four-component reaction, and oxidation of 1,4-DHPs by using NH4VO3 as the catalyst has been developed. NH4VO3 is an efficient, commercially available, inexpensive, and eco-friendly catalyst for these reactions. These methods involve several remarkable advantages, such as simple procedure, mild reaction conditions, short reaction times, high yields, and ease of product isolation.

Data availability
All data generated or analyzed during this study are included in this published article and its supplementary information file. The data is also available through request from corresponding author.

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Table 7. Synthesis of pyridine derivatives and 1,4-DHPs in the presence of NH4VO3 as the catalyst a Reaction conditions: aldehyde (1.0 mmol), ethyl acetoacetate (2.0 mmol), ammonium acetate (2.0 mmol), AcOH (3.0 mL), NH4VO3 (117.0 mg), under air condition. bReaction conditions: 1,4-dihydropyridines (1.0 mmol), AcOH (3.0 mL), NH4VO3 (117.0 mg), under air condition. cReaction conditions: aldehyde (1.0 mmol), ethyl acetoacetate (2.0 mmol), ammonium acetate (2.0 mmol), EtOH (3.0 mL), NH4VO3 (15.0 mg). dIsolated yields.

| Entry | Aldehyde (1) | Product (5) Path A | Product (5) Path B | Mp (°C) of Product (5) | Product (4) | Mp (°C) of Product (4) |
|-------|-------------|-------------------|-------------------|-----------------------|-------------|-----------------------|
|       |             | Time (min) | Yieldd (%) | Time (min) | Yieldd (%) | Time (min) | Yieldd (%) | Time (min) | Yieldd (%) |
| 13    | Thiophen-2-carbaldehyde |          |           |           |           |           |           |           |           |
|       |             | 40        | 75        | 10        | 98        | 15        | 97        |            |            |
| 14    | Cinnamaldehyde | 10        | 65        | 25        | 80        | 20        | 98        |            |            |
| 15    | Terephthalaldehyde | 180       | 83        | 180       | 90        | 30        | 97        |            |            |
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Author contributions

J.R.: main researcher, first author, main laboratory’s performer, wrote the main manuscript and prepared all figures. M.N.: Formal analysis, Visualization, Writing - Review and Editing, Laboratory colleague and prepared all figures. M.H.: co-author in writing the main manuscript. M.N.: Laboratory colleague. H.A.: Laboratory colleague. M.T.I.: Laboratory colleague. A.M.: supervisor and main reviewer.

Competing interests

The authors declare no competing interests.
