Metal Nitrate Catalysis for Selective Oxidation of 5-Hydroxymethylfurfural into 2,5-Diformylfuran under Oxygen Atmosphere

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ABSTRACT: Selective synthesis of various versatile compounds from biomass is of great importance to displace traditional fossil fuel resources. Here, homogeneous metal nitrate (M(NO₃)ₓ)/2,2,6,6-tetramethylpiperidin-1-yl)oxyl (TEMPO) and M(NO₃)ₓ/TEMPO/NaNO₂ catalyst systems in glacial acetic acid and tert-butyl alcohol (TBA) were studied. Meanwhile, the catalyst systems had also good performance for aerobic oxidation of other alcohols.

INTRODUCTION

Biomass was considered by experts as the only renewable source of energy, and it had the potential to replace petroleum in manufacturing chemicals and liquid transportation fuels. Conversion of bio-sourced saccharides to high value-added chemicals has attracted much attention in recent years. As an important bio-based platform chemical, 5-hydroxymethylfurfural (HMF) can be converted to various high value-added products through a variety of reactions including hydrolysis, oxidation, and hydration. TEMPO/NaNO₂ catalytic systems based on M(NO₃)ₓ and M(NO₃)ₓ/NaNO₂ under mild, aerobic conditions (Scheme 1). The oxidations were carried out in glacial acetic acid and 1,4-dioxane.

RESULTS AND DISCUSSION

Our study commenced with screening the transformation of HMF to DFF in the presence of different metal nitrates using molecular oxygen as the oxidant. We initially tried this aerobic oxidation of HMF to DFF using pure O₂ or even O₂ in air as the oxidant. The catalytic methods enable full HMF conversion with a nearly 100% DFF selectivity at 50 °C under atmospheric pressure using a very simple reaction setup and workup. Mechanistic aspects are discussed. The influences of reaction conditions such as different metal catalysts, catalyst loading, solvents, and reaction temperature on the promotion effect were studied. Meanwhile, the catalyst systems had also good performance for aerobic oxidation of other alcohols.

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and attached to a flask containing a solution of HMF. To shorten the reaction time, the reaction temperature was raised to 50 °C (Table 1, entry 2). Under lower Fe(NO₃)₃·9H₂O loading at 2 mol %, 78% yield of DFF was achieved (Table 1, entry 1). Oxygen was simply smoothly at room temperature under atmospheric pressure and attached to a balloon and employed 1 atm (Scheme 1, entry 3). Only a trace amount of the product was detected in a control experiment without the Fe(NO₃)₃·9H₂O catalyst (Table 1, entry 1). Oxygen was simply attached to a balloon and employed 1 atm (Scheme 1, entry 2). Under lower Fe(NO₃)₃·9H₂O worked only as well as Fe(NO₃)₃·9H₂O (Table 1, entry 9). The surprising result may be due to the identical amount of NO₃⁻ in Fe(NO₃)₃·9H₂O and Al(NO₃)₃·9H₂O. To test the hypothesis, we increased the amount of the catalysts Cu(NO₃)₂·3H₂O, Zn(NO₃)₂·6H₂O, HNO₃, KNO₃, and NaNO₃. It was easily found in Table 1 that conversions of the aerobic oxidation were in proportion to the amount of NO₃⁻. The efficiency of HNO₃ or other metals (Cu, Zn) containing nitrates as a viable alternative to Fe(NO₃)₃·9H₂O was also quite surprising (Table 1, entries 12, 15). The results indicated that the metal cation also has some influence on the reaction, and the active species in the M(NO₃)₃/TEMPO catalytic system, maybe, is not the free nitrosonium ion but the metal−TEMPO complex. The coordination of TEMPO to a Lewis acid makes TEMPO a better oxidant. We suggested that the transformation proceeds via a mechanism involving concerted proton-coupled electron transfer from the C−H bond of HMF to the nitrogen atom of the metal−TEMPO complex.

Controlled experiments with or without TEMPO confirmed their necessity to obtain a desired outcome of the reaction. When Fe(NO₃)₃·9H₂O was used without TEMPO, only little HMF was oxidized (Table 2, entry 1), indicating that TEMPO participated in the aerobic oxidation. Subsequently, increasing the amount of TEMPO to 2 mol % resulted in a significant increase in terms of the product yield (Table 2, entry 2). Five mole percent TEMPO was enough for complete transformation of HMF to DFF. Air has the obvious advantage of safety and low cost. We next examined the ability of the Fe(NO₃)₃·9H₂O catalyst to catalyze the HMF oxidation using air instead of pure oxygen as the terminal oxidant. To our delight, DFF was still obtained in a high yield of 81% after 5 h, and the selectively of DFF was even higher (Table 2, entry 4). The lower DFF yield with air balloon was due to a lower oxidation. Alkali-metal nitrates such as sodium nitrate and potassium nitrate presented less catalytic activity (Table 1, entries 8, 11, and 17). By employing 15 mol % NO₃⁻ in combination of TEMPO, 100% HMF conversion was obtained within 5 h with the highest DFF yield of 99%, which was complete oxidations. As far as we are aware, aluminum and zinc were applied here for the first time to mediate efficiently the TEMPO-catalyzed aerobic selective oxidation of HMF to DFF. The observation that Al(NO₃)₃·9H₂O and Zn(NO₃)₂·6H₂O, which contain redox-inactive Al and Zn, are competent catalysts demonstrates that a redox change at the metal is not necessary for HMF oxidation. 

### Table 1. Effect of Different Catalysts on HMF Conversion and DFF Yield in AcOH

| entry | catalyst, loading (mol %) | T (°C) | time (h) | conv. HMF (%) | yield DFF (%) | select (%) |
|-------|--------------------------|--------|----------|--------------|---------------|------------|
| 1     | Fe(NO₃)₃·9H₂O, 5         | RT     | 8        | 100          | 93            | 93         |
| 2     | Fe(NO₃)₃·9H₂O, 5         | 50     | 5        | 100          | 95            | 95         |
| 3     | Fe(NO₃)₃·9H₂O·2          | 50     | 5        | 84           | 78            | 78         |
| 4     | Fe(acac)₃, 5             | 50     | 5        | 2            | 1             | 1          |
| 5     | Fe(acac)₃, 5             | 50     | 5        | 23           | 21            | 21         |
| 6     | FeCl₃·6H₂O, 5            | 50     | 5        | 2            | 1             | 1          |
| 7     | Cu(NO₃)₂·3H₂O, 5         | 50     | 5        | 81           | 80            | 80         |
| 8     | Cu(NO₃)₂·3H₂O, 7.5       | 50     | 5        | 100          | 99            | 99         |
| 9     | Al(NO₃)₃·9H₂O, 5         | 50     | 5        | 95           | 93            | 93         |
| 10    | Zn(NO₃)₂·6H₂O, 5         | 50     | 5        | 78           | 72            | 72         |
| 11    | Zn(NO₃)₂·6H₂O, 7.5       | 50     | 5        | 100          | 97            | 97         |
| 12    | KNO₃, 10                 | 50     | 5        | 49           | 57            | 57         |
| 13    | KNO₃, 15                 | 50     | 5        | 64           | 61            | 61         |
| 14    | NaNO₃, 10                | 50     | 5        | 51           | 49            | 49         |
| 15    | NaNO₃, 15                | 50     | 5        | 64           | 62            | 62         |
| 16    | HNO₃, 5                  | 50     | 5        | 72           | 71            | 71         |
| 17    | HNO₃, 15                 | 50     | 5        | 100          | 98            | 98         |

*Reaction conditions: HMF (1 mmol, 126 mg), TEMPO (0.05 mmol, 7.8 mg), 50 °C, AcOH (2 mL), and oxygen balloon; the conversion and yield were determined by HPLC. Conv. = conversion. Select. = selectivity. DFF (%) = yield (DFF)/conversion (HMF).*

### Table 2. Effect of Cocatalysts and Oxidants on HMF Conversion and DFF Yield in AcOH

| entry | cocatalyst, loading (mol %) | oxidant, (mmol) | time (h) | conv. HMF (%) | yield DFF (%) | select (%) |
|-------|----------------------------|-----------------|----------|--------------|---------------|------------|
| 1     | TEMPO, 0                   | O₂, 5           | 5        | 17           | 0             | 0          |
| 2     | TEMPO, 0                   | O₂, 5           | 5        | 85           | 69            | 81         |
| 3     | TEMPO, 5                   | O₂, 5           | 5        | 100          | 95            | 95         |
| 4     | TEMPO, 5                   | air, 5          | 5        | 82           | 81            | 99         |
| 5     | NH₃, 5                     | O₂, 5           | 24       | 37           | 3             | 8          |
| 6     | DHQ, (2)                   | O₂, 5           | 24       | 18           | 4             | 22         |
| 7     | THQ (2)                    | O₂, 5           | 24       | 46           | 1             | 2          |
| 8     | H₂O₂, (2)                  | O₂, 5           | 24       | 30           | 0             | 0          |

*Reaction conditions: HMF (1 mmol, 126 mg), Fe(NO₃)₃·9H₂O (0.05 mmol), 50 °C, AcOH (2 mL), and oxygen balloon; the conversion and yield were determined by HPLC. Conv. = conversion. Select. = selectivity. DFF (%) = yield (DFF)/conversion (HMF).*
concentration of oxygen. The catalytic efficiency of other stable N-oxyl radical such as N-hydroxyphthalimide (NHPI) replaced TEMPO with 5 mol % Fe(NO₃)₃·9H₂O in AcOH under an oxygen atmosphere at 50 °C, however, exhibited a very small amount of HMF conversion (Table 2, entry 5). Importantly, if other common oxidants such as 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ), t-BuOOH (TBHP), and H₂O₂ were used instead of TEMPO and oxygen, HPLC analysis of the products after 24 h of reaction revealed the further oxidation into 2,5-furandicarboxylic acid (FDCA) (14% yield at 18% HMF conversion). Selectivity was defined as the ratio of the yield of DFF to the conversion of HMF. 

It is known that the solvent is a key factor affecting the reaction efficiency. Thus, the aerobic oxidation of HMF to DFF was carried out in a variety of common solvents such as ethyl acetate (EtOAc) and 1,2-dichloroethane (DCE), which have been used in related alcohol oxidation methods. As shown in Table 3, the solvent showed a remarkable effect on DFF selectivity. Low DFF selectivity was obtained when the reaction was carried out in EtOAc and DCE (Table 3, entries 1 and 2). The concentration of HMF can also have some effects on the conversion of HMF during the oxidation process. When the concentration of HMF was 1 mol/L, after reaction for 5 h, the yield of product DFF was 61% (Table 3, entry 3); nevertheless, when HMF was set at a lower concentration of 0.5 mol/L under the same conditions, full conversion was achieved (Table 3, entry 4), indicating that lowering the HMF concentration, the yields of product DFF can be increased. However, a further reduction in the concentration of HMF to 0.2 mol/L resulted in a lower yield of DFF.

To make the workup procedure more simple and apply to substrates containing acid-sensitive functional groups, the catalytic system of Fe(NO₃)₃/TEMPO was further studied in CH₂CN; however, the reaction was much slower (96% of conversion after 24 h) than that in AcOH. Thus, we started to test the effect of additives: The addition of NaNO₂ helps much increase in reaction rates (Table 4, entry 2). The result demonstrated that NaNO₂ is an activating agent for the iron–TEMPO catalytic system. The cheap and readily available inorganic halide sodium chloride was screened for such a purpose. In our hands, the addition of NaCl (5 mol %) as an additive, as reported by Ma et al., suggests that the reaction was completed within 15 h (Table 4, entry 3). Isobutyl nitrite (C₄H₉NO₂) worked much slower (Table 4, entry 4). In addition, no reaction occurred in the absence of Fe(NO₃)₃·9H₂O (Table 4, entry 5) or TEMPO under oxygen (Table 4, entry 6), suggesting that both Fe(NO₃)₃·9H₂O and TEMPO are required for the reaction. Then, Fe(acac)₃ and FeCl₃ were used as catalysts in the catalytic system, and Fe(acac)₃ was almost inert for the selective oxidation of HMF (Table 4, entry 7). As for FeCl₃, much better conversion (36%) with 100% selectivity was obtained (Table 4, entry 8). For Cu(NO₃)₂·3H₂O, we found that HMF conversion significantly increased from 62 to 100% with increasing catalyst loading (Table 4, entries 9 and 10). Further experiments with Al(NO₃)₃·9H₂O presented a poorer catalytic activity as compared with the case of AcOH as a solvent (Table 4, entry 11). Increasing the amount of Zn(NO₃)₂·6H₂O led to slight conversion of HMF (Table 4, entries 12 and 13). KNO₃ and NaNO₃ were not effective at all for the oxidation of HMF (Table 4, entries 14 and 15). These results clearly showed that employing redox-active metals such as Fe and Cu had a better effect on the reaction outcome in CH₂CN. On the basis of the results of this experiment and the previous reports, a plausible reaction pathway is illustrated in Scheme 2.

### Table 3. Effect of the Solvent and HMF Concentration on HMF Conversion and DFF Yield with Fe(NO₃)₃/TEMPO Catalyst System

| Entry | Solvent | Solvent Amount (mL) | Conversion (%) | Yield DFF (%) | Selectivity (%) |
|-------|---------|--------------------|---------------|--------------|----------------|
| 1     | EtOAc   | 2                  | 100           | 57           | 57             |
| 2     | DCE     | 2                  | 100           | 64           | 64             |
| 3     | AcOH    | 1                  | 62            | 61           | 98             |
| 4     | AcOH    | 2                  | 100           | 95           | 95             |
| 5     | AcOH    | 5                  | 58            | 52           | 90             |

*Reaction conditions: HMF (1 mmol, 126 mg), Fe(NO₃)₃·9H₂O (0.05 mmol), TEMPO (0.05 mmol, 7.8 mg), 50 °C, 5 h, and oxygen balloon. The conversion and yield were determined by HPLC. Conv. = conversion; Select. = selectivity. (%) (DFF) = yield (DFF)/conversion (HMF)*

### Table 4. Effect of Different Catalysts on HMF Conversion and DFF Yield in CH₂CN

| Entry | Catalyst, Loading (mol %) | Cocatalyst | Additive | Time (h) | Conv. HMF (%) | Yield DFF (%) | Selectivity (%) |
|-------|--------------------------|------------|----------|---------|---------------|---------------|----------------|
| 1     | Fe(NO₃)₃·9H₂O, 5         | TEMPO      | NaNO₂    | 24      | 96            | 91            | 95             |
| 2     | Fe(NO₃)₃·9H₂O, 5         | TEMPO      | NaNO₂    | 10      | 100           | 94            | 94             |
| 3     | Fe(NO₃)₃·9H₂O, 5         | TEMPO      | NaCl     | 15      | 99            | 98            | 98             |
| 4     | Fe(NO₃)₃·9H₂O, 5         | TEMPO      | C₄H₉NO₂  | 24      | 58            | 58            | 100            |
| 5     | Fe(NO₃)₃·9H₂O, 5         | TEMPO      | NaNO₂    | 24      | NR            |               |                |
| 6     | Fe(NO₃)₃·9H₂O, 5         | TEMPO      | NaNO₂    | 24      | 2             | 0             | 0              |
| 7     | Fe(acac)₃, 5             | TEMPO      | NaNO₂    | 24      | 36            | 36            | 100            |
| 8     | FeCl₃·6H₂O, 5            | TEMPO      | NaNO₂    | 24      | 62            | 61            | 98             |
| 9     | Cu(NO₃)₂·3H₂O, 5         | TEMPO      | NaNO₂    | 10      | 100           | 99            | 99             |
| 10    | Cu(NO₃)₂·3H₂O, 7.5       | TEMPO      | NaNO₂    | 10      | 77            | 77            | 100            |
| 11    | Al(NO₃)₃·9H₂O, 5         | TEMPO      | NaNO₂    | 10      | 61            | 60            | 98             |
| 12    | Zn(NO₃)₂·6H₂O, 5         | TEMPO      | NaNO₂    | 10      | 68            | 65            | 96             |
| 13    | Zn(NO₃)₂·6H₂O, 7.5       | TEMPO      | NaNO₂    | 10      | 5             | 1             | 20             |
| 14    | NaN₃·5H₂O               | TEMPO      | NaNO₂    | 10      | 2             | 1             | 50             |

*Reaction conditions: HMF (1 mmol, 126 mg), additive (0.05 mmol), CH₂CN (5 mL), 50 °C, and oxygen balloon. NR = no reaction. The conversion and yield were determined by HPLC. Conv. = conversion; Select. = selectivity. (%) (DFF) = yield (DFF)/conversion (HMF).*
mechanism, by the oxidation action of FeIII or CuII, TEMPO is transformed into a nitrogen carbonyl cation by a single-electron oxidation, and this cation extracts a hydrogen atom from HMF to transform it to DFF. Furthermore, TEMPO is restored to its original state, whereas the FeIII or CuII ion is reduced to the FeII or CuI ion. At the same time, the NO3°− ion oxidizes the FeII or CuI ion to the FeIII or CuII ion, whereas the NO3− ion is reduced to the NO2− ion. In the meantime, molecular oxygen again oxidizes the NO2− ion, and the NO3− ion is thus restored.

Switching from pure oxygen to air and using the same atmospheric pressure also gave the oxidized product DFF in 88% yield after 10 h (Table 5, entry 1). NHPI provided a low conversion under our reaction conditions compared with the reported literature (Table 5, entry 2). These results demonstrated that the catalytic activity of NHPI was not so effective to selectively oxidize HMF to DFF under the present reaction conditions. Both HMF conversion and the selectivity of DFF were low using H2O2 as an oxidant (Table 5, entry 4). Moderate HMF conversion and the DFF yield were obtained using i-ButOOH as an oxidant (Table 5, entry 5), which was different from the reaction in AcOH.

To further investigate the catalytic performance of Fe(NO3)3/TEMPO/NaNO2 aerobic oxidations with different temperatures were carried out in acetonitrile. As shown in Table 6, it was observed that temperature played an important role in the oxidation of HMF in acetonitrile. As expected, HMF conversion and the DFF yield increased with the increase of reaction temperature from room temperature to 50 °C (Table 6, entries 1–4), but a rise over 50 °C resulted in a sharp decline in HMF conversion (Table 6, entries 5 and 6). It could be concluded that the higher temperature (above 50 °C) could result in a negative effect, and 50 °C was the preferred temperature for the Fe(NO3)3/NaNO2/TEMPO catalytic system. Importantly, the selectivity to DFF remained at a relatively constant and high level (>94%) while the reaction temperatures were varied. The decline in the yield of DFF over 50 °C may possibly be attributed to the mass transfer resistance of oxygen from oxygen gas on the liquid surface down to the liquid solution. Larger mass transfer resistance of oxygen makes the concentration of oxygen lower, and as a consequence, fewer HMF molecules will be successfully transformed into DFF.

The solvent effect of the aerobic oxidation reaction at 50 °C was examined to select an industrial friendly solvent. The results of the oxidation of HMF in the presence of 5 mol % Fe(NO3)3·9H2O, 5 mol % TEMPO, and 5 mol % NaNO2 under the atmospheric pressure of oxygen in different solvents are summarized in Table 7. We were delighted to find that when using ethyl acetate as the solvent, HMF could be converted into DFF within 10 h in an almost quantitative yield of 98%. Therefore, ethyl acetate is also a desired solvent. Under the same conditions, the conversion of HMF to DFF was achieved in a high yield in 1,2-dichloroethane. However, such an environmentally unfriendly chlorinated solvent is disfavored for large-scale industrial application. The effect of the substrate concentration on the conversion of HMF and the yield/selectivity of DFF is shown in Table 8. As the substrate

![Scheme 2. Proposed Catalytic Cycle for Aerobic Oxidation of HMF with M(NO3)3/TEMPO/NaNO2](image)

Table 5. Effect of Cocatalysts and Oxidants on HMF Conversion and DFF Yield in CH3CN

| entry | cocatalyst, loading (mol %) | oxidant | time (h) | conv. HMF (%) | yield DFF (%) | select. (%) |
|-------|---------------------------|---------|----------|---------------|---------------|-------------|
| 1     | TEMPO, 5                  | air     | 10       | 89            | 88            | 99          |
| 2     | NHPI, 5                   | O2      | 24       | 57            | 54            | 95          |
| 3     | DDQ                       | D2O2    | 10       | 32            | 19            | 59          |
| 4     | H2O2                      |         | 24       | 11            | 6             | 55          |
| 5     | TBHP                      |         | 24       | 64            | 58            | 91          |

*Reaction conditions: HMF (1 mmol, 126 mg); Fe(NO3)3·9H2O (0.05 mmol), NaNO2 (0.05 mmol, 3.4 mg), CH3CN (5 mL), and oxygen balloon; the conversion and yield were determined by HPLC. Conv. = conversion. Select. = selectivity. S (DFF) = yield (DFF)/conversion (HMF).

Table 6. Effect of Reaction Temperature on HMF Conversion and DFF Yield in CH3CN

| entry | temperature (°C) | conv. HMF (%) | yield DFF (%) | select. (%) |
|-------|------------------|---------------|---------------|-------------|
| 1     | RT               | 16            | 15            | 94          |
| 2     | 30               | 57            | 55            | 96          |
| 3     | 40               | 72            | 69            | 95          |
| 4     | 50               | 100           | 94            | 94          |
| 5     | 60               | 54            | 52            | 96          |
| 6     | 70               | 28            | 27            | 96          |

*Reaction conditions: HMF (1 mmol, 126 mg); Fe(NO3)3·9H2O (0.05 mmol), TEMPO (0.05 mmol, 7.8 mg), NaNO2 (0.05 mmol, 3.4 mg), CH3CN (5 mL), and oxygen balloon; the conversion and yield were determined by HPLC. Conv. = conversion. Select. = selectivity. S (DFF) = yield (DFF)/conversion (HMF).

Table 7. Effect of the Solvent and HMF Concentration on HMF Conversion and DFF Yield with Fe(NO3)3/NaNO2/TEMPO Catalyst System Conditions

| entry | solvent amount (mL) | conv. HMF (%) | yield DFF (%) | select. (%) |
|-------|---------------------|---------------|---------------|-------------|
| 1     | H2O                 | 55            | 51            | 93          |
| 2     | EtOAc               | 5             | 3             | 100         |
| 3     | DCE                 | 5             | 100           | 93          |
| 4     | MeCN                | 5             | 100           | 94          |
| 5     | MeCN                | 2             | 100           | 96          |
| 6     | MeCN                | 1             | 80            | 77          |

*Reaction conditions: HMF (1 mmol, 126 mg); Fe(NO3)3·9H2O (0.05 mmol, 20 mg), TEMPO (0.05 mmol, 7.8 mg), NaNO2 (0.05 mmol, 3.4 mg), 50 °C, 10 h, and oxygen balloon; the conversion and yield were determined by HPLC. Conv. = conversion. Select. = selectivity. S (DFF) = yield (DFF)/conversion (HMF).
concentration increased from 0.2 mol/L to 0.5 mol/L, almost no change was observed in the DFF yield (Table 7, entries 5 and 6). As the concentration of HMF was further increased to 1 mol/L, the conversion of HMF decreased to 80%, which is most likely due to the evaporation of CH₃CN and the mass transfer of the entire system being restricted by the increase in the substrate concentration.

The two catalyst systems were applied to the aerobic oxidation of a variety of alcohols. As shown in Table 8, all benzylic alcohols were quantitatively converted into the corresponding aldehydes with >99% selectivity with both of the catalyst systems. Secondary alcohols including cyclohexanol and diphenylmethanol can be completely converted into corresponding ketones with >99% selectivity with the Fe(NO₃)₃/TEMPO catalytic system in CH₃CN, whereas the secondary aliphatic alcohol cyclohexanol was failed to afford the desired product with the Fe(NO₃)₃/TEMPO catalytic system in AcOH. 1,2-Diols seldom interfered with the catalytic aerobic oxidation were selectively oxidized into ketone and aldehyde. 1,2-Diols were cleanly oxidized to α-dicarbonyl without cleavage of the 1,2-diol bond with the Fe(NO₃)₃/TEMPO/NaNO₂ catalytic system in CH₃CN, whereas the secondary aliphatic alcohol cyclohexanol was failed to afford the desired product with the Fe(NO₃)₃/TEMPO catalytic system in AcOH. 1,2-Diols seldom interfered with the catalytic aerobic oxidation were selectively oxidized into ketone and aldehyde. 1,2-Diols were cleanly oxidized to α-dicarbonyl without cleavage of the 1,2-diol bond with the Fe(NO₃)₃/TEMPO/NaNO₂ catalytic system in CH₃CN, whereas the secondary aliphatic alcohol cyclohexanol was failed to afford the desired product with the Fe(NO₃)₃/TEMPO catalytic system in AcOH.

**CONCLUSIONS**

We have developed two novel catalytic systems, including TEMPO and metal nitrates, for the aerobic oxidation of HMF to DFF at 50 °C in the presence of 1 atm O₂. Various aliphatic and aromatic alcohols could be oxidized quantitatively to the corresponding carbonyl compounds in the catalytic systems, and pure products are generally isolable by simple extraction with an organic solvent and water. We anticipated that this protocol will be of broad interest and use to the chemical industries.

**EXPERIMENTAL SECTION**

**Materials.** All chemicals used in this study were of analytical reagent grade, commercially available, and used without further purification unless otherwise noted. Reactions were carried out in 5 or 10 mL glass flasks. HMF and balloons (500 mL) were purchased from Sigma-Aldrich and used as an air reservoir. Reactions were monitored using thin-layer chromatography on TLC silica gel 60 F254 aluminum sheets (20 × 20 cm).

**Selective Aerobic Oxidation of Alcohols into Aldehydes or Ketones with the M(NO₃)₃/TEMPO Catalytic System.** For a typical procedure, a 5 mL glass flask equipped with a magnetic stirring bar was charged with HMF (126 mg, 1 mmol) and glacial acetic acid (2 mL). Fe(NO₃)₃·9H₂O (20.2 g/mol) was added to the flask, and the mixture was then heated to 50 °C under an atmosphere of oxygen for 10 h. After cooling to room temperature, the reaction mixture was diluted with EtOAc (20 mL) and washed with saturated Na₂CO₃ solution (2 × 20 mL) and brine (2 × 20 mL). The organic layer was dried over Na₂SO₄ and concentrated under reduced pressure. The crude product was purified by silica gel column chromatography to afford the desired product. The yield and product purity were determined by GC with area normalization.
mg, 0.05 mmol) and TEMPO (7.8 mg, 0.05 mmol) were consecutively added to the solution, and a balloon filled with oxygen (500 mL) was then attached to the flask. The reaction mixture was magnetically stirred at 50 °C, and the consumption of the starting material was monitored using TLC. After completion of the reaction, the reaction was quenched by adding EtOAc. The catalyst was removed by washing with water. Aqueous phases were combined and then extracted with EtOAc. The aqueous phase extracts were then combined and dried with MgSO₄. The solvent was evaporated in vacuo to yield pure products.

**Selective Aerobic Oxidation of Alcohols into Aldehydes or Ketones with the M(NO₃)ₓ/TEMPO/NaNO₂ Catalytic System.** For a typical procedure, HMF (126 mg, 1 mmol), Fe(NO₃)₃·9H₂O (20.2 mg, 0.05 mmol), TEMPO (7.8 mg, 0.05 mmol), NaNO₂ (3.4 mg, 0.05 mmol), and CH₃CN (5 mL) were added to a 10 mL glass flask. The resulting mixture was stirred under the atmosphere of oxygen from a balloon at 50 °C until HMF disappeared (as monitored by TLC). Upon completion, the reaction was quenched by adding EtOAc. The catalyst was removed by washing with water. The aqueous phases were combined and extracted with EtOAc. The aqueous phase extracts were then combined and dried with MgSO₄. The solvent was evaporated in vacuo to yield pure products.

**Product Analysis.** HMF and DFF were analyzed by HPLC using a reversed-phase C18 column (250 × 4.6 mm) at 25 °C with a detection wavelength of 280 nm. The mobile phase was acetonitrile and 0.1 wt % acetic acid aqueous solution (65:35 v/v) at 0.5 mL/min. The HMF conversion and DFF yield were expressed as mol % in terms of the total HMF amount. The amounts of HMF and DFF in the samples were calculated by interpolation from calibration curves. Calibration curves for the amounts of HMF and DFF in the samples were calculated by injecting known amounts of HMF and DFF into the innovative fuels and chemicals.

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**Notes**

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