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Graphical Abstract

Catalytic Aerobic Oxidation of Renewable Furfural to Maleic Anhydride and Furanone Derivatives and Their Mechanistic Studies

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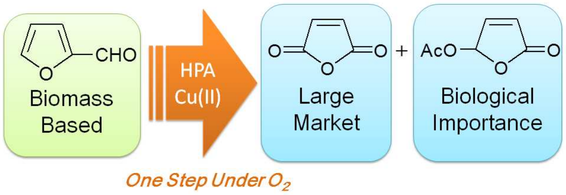
Using heteropolyacid and copper(II) as catalysts, the renewable furfural has been successfully transformed to maleic anhydride and biologically important 5-acetoxyl-2(5H)-furfuran.



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Catalytic Aerobic Oxidation of Renewable Furfural to Maleic Anhydride and Furanone Derivatives with Their Mechanistic Studies

Jihong Lan§, Zhuqi Chen§, Jinchi Lin, Guochuan Yin*

Catalytic transformation of biomass based furfural to valorized chemicals is an alternative route to the on-going fossil feedstock based processes. This work describes catalytic aerobic oxidation of furfural to maleic anhydride, an important polymer starting materials having large market, with $H_5PV_2Mo_{10}O_{40}$ and $Cu(CF_3SO_3)_2$ catalysts. Under the optimized conditions, 54.0% yield of maleic anhydride can be achieved with about 7.5% yield of 5-acetoxyl-2(5H)-furanone formation. Notably, 5-acetoxyl-2(5H)-furanone is a highly valorized, biologically important intermediate which has been applied in pharmaceutical synthesis. The catalytic mechanism for furfural oxidation to maleic anhydride and 5-acetoxyl-2(5H)-furanone has been investigated in detail with identifications of several key intermediates.

Introduction

Biomass, dominantly comprised of carbon, hydrogen, oxygen and nitrogen, is the largest, renewable carbon resources on earth. With the diminishing of the fossil resources, biomass has been regarded as a promising feedstock for the chemical industry in the future[1]. In exploring new chemicals from polysaccharides, C6 based biomass and its sub-products have been fully recognized[2], while the explorations of C5 based resources are still very limited. Compared with C6 based HMF, its analog, C5 based furfural comes from rich agricultural materials like corncobs, oat, wheat bran, and sawdust etc., and they are not competitive with human beings. Particularly, unlike HMF which is currently synthesized in lab scale, furfural production is an on-going industrial process, therefore, exploring the sub-products using furfural as the platform to replace the fossil resources is greatly attractive [3].

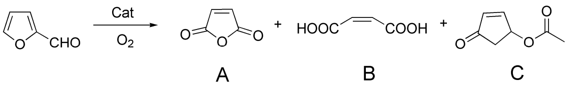
Maleic anhydride is a starting material for the manufacture of unsaturated polyester resins and many other important chemicals[4]. Currently, maleic anhydride is commercially produced by catalytic oxidation of petroleum-derived chemicals such as n-butane and benzene in millions of ton annually[5]. With the depletion of petroleum feedstock and environmental concerns associated with the petroleum industry, it has been leading to the technology transitions from petroleum to biomass, a greener and more renewable feedstock[6]. As early as in 1926, Sessions had demonstrated the vapor phase oxidation of furfural to maleic anhydride in the presence of V_2O_5 catalyst at 200~300 ℃ [7], and in 1947, Nielsen introduced an iron molybdate catalyst which can provide more than 70% selectivity of maleic anhydride based on converted furfural by vapor phase oxidation. However, continuing studies on transformations of furfural to maleic anhydride were very limited, possibly due to its poor competition with the petroleum based on-going processes. Recently, Ojeda applied VO_x/Al_2O_3 as solid catalysts for vapor phase oxidation of furfural, which provides a considerably high yield (73%) of maleic anhydride under 593 K[8]. Combining with earlier mechanistic studies using solid catalysts like $Sn(VO_3)_4$ and promoted V-Mo-P like P_2O_5, $Fe_2(MoO_4)_3$, MoO_3, V_2O_5[9–12], Ojeda proposed that decarbonylation is the first step in furfural vapor phase oxidation which generates furan as the intermediate, then followed by further oxidation of furan to maleic anhydride.

In 2011, we reported the aerobic oxidation of furfural to maleic acid in aqueous solution using heteropolyacid catalysts[13], in which phosphomolybdic acid, $H_3PMo_{12}O_{40}$, plus copper(II) nitrate as catalyst demonstrates considerably high catalytic activity, providing 50% yield of maleic acid. To further improve the selectivity of maleic acid and potentially recycling of catalyst and unconverted furfural, we further built up an aqueous/organic biphase system in which phosphomolybdic acid alone as catalyst could provide 68% selectivity of maleic acid[14]. The relatively high selectivity was achieved by that, with the oxidation proceeding, hydrophobic furfural was slowly released through phase equilibrium from organic phase into aqueous phase where the oxidation reaction happens. However, due to the oxidation was carried out in aqueous phase, there was no maleic anhydride product observed. Compared with maleic acid, maleic anhydride has a much larger market due to its wide applications in polymer industry. Here, we report a furfural based maleic anhydride synthesis in liquid phase, and its catalytic transformation mechanism has been elucidated, which is apparently different from those in vapor phase oxidation. Notably, a highly valorized, biological important product, 5-acetoxyl-2(5H)-furanone, was unexpectedly co-produced under the catalytic conditions.

Results and discussion

Catalyst scanning for furfural oxidation

The catalytic reactivity of heteropolyacids has attracted much attention in redox chemistry, and they were also employed in our recent furfural oxidations and one of these author's earlier studies on oxidative carbonylation of phenol to diphenyl carbonate [13-15]. To avoid the hydrolysis of maleic anhydride, here, catalytic oxidations of furfural were performed in organic solvent, and a list of heteropolyacids were tested as catalyst. The reaction was performed under pressured oxygen (20 atm) in acetonitrile/acetic acid (2:1.3, v/v) at 383 K. Through GC-MS analysis of the reaction mixtures after oxidation, three products including maleic anhydride (**A**), maleic acid (**B**) and 5-acetoxyl-2(5H)-furanone (**C**) were identified as illustrated in Eq. 1. Among the heteropolyacids tested in Table 1, vanadium(V) substituted heteropolyacid, $H_5PV_2Mo_{10}O_{40}$, demonstrates the highest catalytic activity for furfural oxidation. After 14 h reaction, 93.8% conversion of furfural could be achieved with $H_5PV_2Mo_{10}O_{40}$ catalyst, the total yields of three products are 43.5%, including 29.5% yield of maleic anhydride, 9.8% yield of maleic acid and 4.2% of 5-acetoxyl-2(5H)-furanone (entry 7). When furfural is exposed to air, it generally leads to polymerization, and the color turns black gradually. Here, although the reaction solution remains clean after catalytic oxidation, it does not exclude the formation of certain oligomers under the pressured oxygen with elevated temperature, which leads to relatively low yield of three major products. Particularly, formation of 5-acetoxyl-2(5H)-furanone was absolutely unexpected, which costs these authors a lot of time to isolate and characterize it, and finally it was identified by GC-MS and NMR analysis. The unique carbon skeleton of 2(5H)-furanone is biologically important and widely present in a variety of natural products, and the pharmaceutical synthesis based on 2(5H)-furanones has attracted much attention recently[16]. Under the optimized conditions, that is, adding minor acetic anhydride to acetonitrile/acetic acid (2/1.3, v/v) solvent mixture, the yield of 5-acetoxyl-2(5H)-furanone can be improved up to 11.4% (see Table S1 in supporting information). Even that the yield of 5-acetoxyl-2(5H)-furanone is not as high as that of maleic anhydride in this catalytic system, directly transformation of renewable furfural to the highly valorized, biologically important pharmaceutical intermediate, 2(5H)-furanone, is of great interest for its potentially commercial manufacture.



Eq. 1

Table 1. Catalyst scanning for furfural oxidation

Entry	HPA	Cu(II) (mmol)	Conv. (%)	Yield A(%)	Yield B(%)	Yield C(%)	Yield[b] (%)
1	$H_3PMo_{12}O_{40}\cdot xH_2O$	/	51	0.3	<0.1	<0.1	0.4
2	$H_3PMo_{12}O_{40}\cdot xH_2O$	0.02	34.9	1.2	1.9	0.3	3.4
3	$H_3PW_{12}O_{40}\cdot xH_2O$	/	15.4	0.1	0.1	<0.1	0.2
4	$H_3PW_{12}O_{40}\cdot xH_2O$	0.02	39.4	0.3	<0.1	0.3	0.6
5	$H_4[SiO_4(W_3O_9)_4]\cdot xH_2O$	/	44.2	0.4	<0.1	0.1	0.5
6	$H_4[SiO_4(W_3O_9)_4]\cdot xH_2O$	0.02	50.1	0.4	0.1	0.5	1.0
7	$H_5PV_2Mo_{10}O_{40}\cdot xH_2O$	/	93.8	29.5	9.8	4.2	43.5
8	$H_5PV_2Mo_{10}O_{40}\cdot xH_2O$	0.02	98.7	54.0	/	7.5	61.5
9	$H_4PVMo_{11}O_{40}\cdot xH_2O$	/	53.7	0.3	4.4	1.5	6.2
10	$H_4PVMo_{11}O_{40}\cdot xH_2O$	0.02	72.7	13.9	2.0	4.2	20.1
11	$H_6PV_3Mo_9O_{40}\cdot xH_2O$	/	97.3	25.9	10.3	7.4	43.6
12	$H_6PV_3Mo_9O_{40}\cdot xH_2O$	0.02	99.1	30.3	12.1	6.8	49.2

[a] Conditions: 0.02 mmol heteropolyacid, 0.02 mmol $Cu(CF_3SO_3)_2$, 2.4 mmol furfural, 2 mL CH_3CN, 1.3 mL HOAc, 20 atm O_2, 383 K, 14 h. [b] Total yields of maleic acid, maleic anhydride and 5-acetoxyl-2(5H)-furanone.

Remarkably, adding 1 equiv of $Cu(CF_3SO_3)_2$ to the catalytic solution would further improve the yield of maleic anhydride up to 54.0% but with no maleic acid observed in analysis, while the yield of 5-acetoxyl-2(5H)-furanone has also been slightly improved (7.5%) (entry 8). This improvement has also been observed when $H_4PVMo_{11}O_{40}$ and $H_4PV_3Mo_{10}O_{40}$ were used as catalysts. For the $H_4PVMo_{11}O_{40}$ catalyst, the total yields of three products can be sharply improved from 6.2% to 20.1% by adding $Cu(CF_3SO_3)_2$, while for $H_6PV_3Mo_9O_{40}$, the total yields can be improved from 43.6% to 49.2%. For other heteropolyacids, their catalytic activities are pretty poor, and adding copper(II) also does not improve their efficiencies too much under current conditions.

Influence of the additives on furfural oxidation

Recently, redox inactive metal ions serving as Lewis acid in redox transition metal ions mediated oxidations has attracted considerable attentions in communities[17]. After investigating the reactivity relationship of the active intermediates in oxidation, we have also explored Al(III) promoted Pd(II) catalyzed benzene hydroxylation and manganese(II) complexes catalyzed sulfide oxidations[18]. To further pursue the synergistic effect between the $H_5PV_2Mo_{10}O_{40}$ and Lewis acids, a wide range of metal ions were tested as additives in furfural oxidation, and the results are summarized in Table 2.

Table 2. Lewis acids scanning for the furfural oxidation

Entry	Lewis acid	Conversion (%)	Yield A(%)	Yield B(%)	Yield C(%)	Yield[b] (%)
1	/	93.8	29.5	9.8	4.2	43.5
2	$AgCF_3SO_3$	99.5	32.6	13.7	5.9	52.2
3	$NaCF_3SO_3$	98.5	34	9.7	5.4	49.1
4	$Mg(CF_3SO_3)_2$	97.1	29.7	14.3	5.6	49.6
5	$Zn(CF_3SO_3)_2$	100	29.3	11.6	5.9	46.8
6	$Cu(CF_3SO_3)_2$	98.7	54	/	7.5	61.5
7	$Pd(OAc)_2$	94.2	28.6	14.5	5.6	48.7
8	$FeCl_2$	99.4	33.6	10.9	5.7	50.2
9	$Y(CF_3SO_3)_3$	98.5	27.4	19.2	2.3	48.9
10	$Yb(CF_3SO_3)_3$	97.8	28.2	17	2.3	47.5
11	$Sc(CF_3SO_3)_3$	98.2	27.3	15.5	4.8	47.6
12	$Al(CF_3SO_3)_3$	98.8	30.5	10.6	3.3	44.4

[a] Conditions: 0.02 mmol $H_5PV_2Mo_{10}O_{40}\cdot xH_2O$, 0.02 mmol Lewis acid, 2.4 mmol furfural, 2 mL CH_3CN, 1.3 mL HOAc, 20 atm O_2, 383 K, 14 h. [b] Total yields of maleic acid, maleic anhydride and 5-acetoxyl-2(5H)-furanone

Apparently, the catalytic activity of $H_5PV_2Mo_{10}O_{40}$ can be improved by adding Lewis acids in each case. For example, the total yields of three listed products can be improved up to 52.2% for $AgCF_3SO_3$, 50.2% for $FeCl_2$ and 48.9% for $Y(CF_3SO_3)_3$, respectively, while $H_5PV_2Mo_{10}O_{40}$ alone gives 43.5% of total yields. Particularly, adding $Cu(CF_3SO_3)_2$ leads to the highest total yield (61.5%). However, adding Cu(II) also leads to the disappearance of maleic acid as product, whereas other metal ions may improve the maleic acid formation in most cases. For example, Y(III) as additives provides 19.2% yield of maleic acid, while it is 9.8% for $H_5PV_2Mo_{10}O_{40}$ as catalyst alone.

Table 3. The stability of maleic acid & anhydride under dehydration process

Entry	Lewis acid	Starting maleic acid (g)	Starting maleic anhydride(g)	After reflux[b] (g)	Loss(%)
1	/	/	0.1022	0.1025	0
2	/	0.1051	/	0.0879 /(0.0888)[c]	1
3	$Cu(CF_3SO_3)_2$	/	0.1022	0.0855	16.6
4	$Cu(CF_3SO_3)_2$	0.1051	/	0.0692 /(0.0888)[c]	21.3
5	$AgCF_3SO_3$	/	0.1149	0.1154	0
6	$AgCF_3SO_3$	0.116	/	0.0983 /(0.0980)[c]	0
7	$Sc(CF_3SO_3)_3$	/	0.1149	0.1127	1.9
8	$Sc(CF_3SO_3)_3$	0.116	/	0.098 /(0.0980)[c]	0

[a] Conditions: 0.02 mmol $H_5PV_2Mo_{10}O_{40}$, 0.02 mmol Lewis acid, 2 mL CH_3CN, 1.3 mL HOAc, 5 mL Ac_2O, 373 k , 2 h. [b] The mass of maleic anhydride. c The theoretical mass of maleic anhydride generated.

Since the quantitative analysis of maleic acid was conducted after dehydration of the reaction mixtures by adding acetic anhydride to generate maleic anhydride under reflux conditions (independent analysis of maleic anhydride and 5-acetoxyl-2(5H)-furanone products was performed prior to this procedure, see experimental section for details), the presence of copper(II) may cause the decomposition of maleic anhydride and maleic acid during the dehydration process. In complimentary experiments, we investigated the stability of maleic acid and maleic anhydride during the dehydration process, and the results are listed in Table 3. One may see that, with the tested Lewis acids, copper(II) can decompose maleic acid, leading to 21.3% loss of initial maleic acid substrate, while the other two exampled Lewis acids, Ag(I) and Sc(III), does not. Similar decomposition of maleic anhydride was also observed in dehydration procedure when using maleic anhydride in place of maleic acid, which leads to the amount of maleic anhydride after dehydration treatment is less than its original amount, thus makes no formation of maleic acid in calculation when using copper(II) as additives. Other Lewis acids as additives demonstrate the formation of maleic acid because they do not decompose maleic acid and maleic anhydride.

Optimization of furfural oxidation

Table 4. Catalytic efficiency on furfural oxidation by $Cu(CF_3SO_3)_2$ and $H_5PV_2Mo_{10}O_{40}$•xH_2O acid

Entry	$H_5PV_2Mo_{10}O_{40}$ (mmol)	Cu(II) (mmol)	Con (%)	Yield A(%)	Yield B(%)	Yield C(%)	Yield[b] (%)
1	0.01	0.01	98.8	42.1	/	4.8	46.9
2	0.01	/	97.3	33.4	7.9	4.2	45.5
3	0.02	/	93.8	29.5	9.8	4.2	43.5
4	0.03	/	99.2	29.9	10	3.2	43.1
5	/	0.02	22	0.2	<0.1	0.4	0.6
6	0.02	0.02	98.7	54	/	7.5	61.5
7	0.02	0.04	99.4	33.3	/	9.9	43.2
8	0.02	0.08	100	35.1	/	8.9	44
9	0.02	0.32	100	16.7	/	7.8	24.5
10	0.03	0.03	99.5	40.2	/	2	42.2
11	0.04	0.04	99	33	/	1.8	34.8
12	0.08	0.16	100	13.3	/	6.8	20.1

[a] Reaction condition: 2.4 mmol furfural, 2 mL CH_3CN, 1.3 mL HOAc, 20 atm O_2, 383 K, 14 h. [b] Total yield of maleic acid, maleic anhydride and 5-acetoxyl-2(5H)furanone.

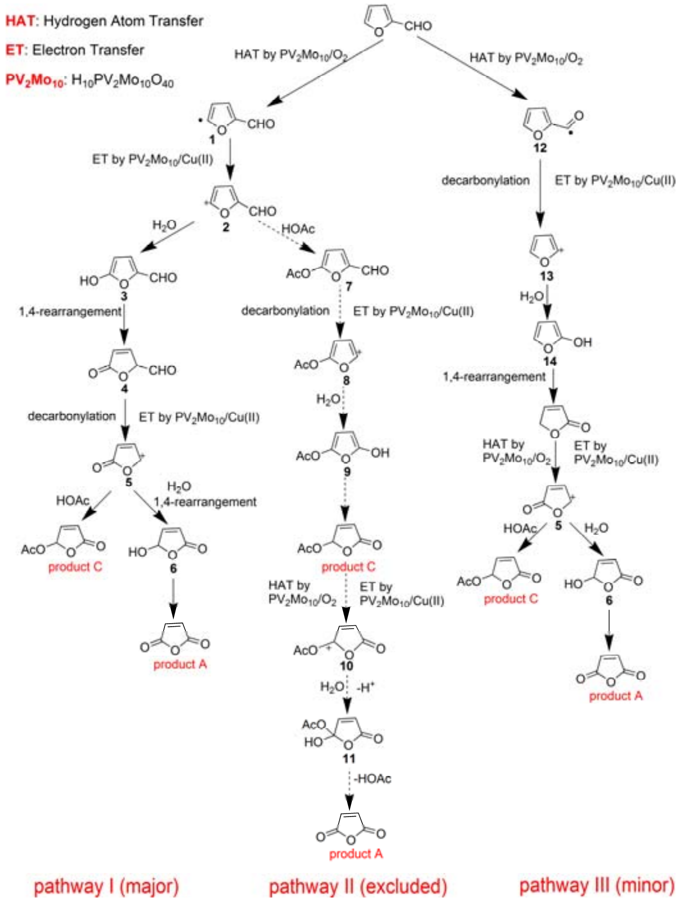
The influence of the ratio between $H_5PV_2Mo_{10}O_{40}$ and Cu(II) on catalytic activity was next investigated and listed in Table 4. When $H_5PV_2Mo_{10}O_{40}$ was employed as catalyst alone, different catalyst concentrations provide a similar activity. That is, the total yields were 45.5%, 43.5% and 43.1% under the $H_5PV_2Mo_{10}O_{40}$ loading of 0.01, 0.02 and 0.03 mmol (entries 2, 3 and 4), respectively. Also, the selectivities of products were similar. For example, the yields of product maleic anhydride, maleic acid and 5-acetoxyl-2(5H)-furanone are 33.4%, 7.9% and 4.2% by 0.01 mmol of $H_5PV_2Mo_{10}O_{40}$, and 29.5%, 9.8% and 4.2% by 0.02 mmol of $H_5PV_2Mo_{10}O_{40}$, respectively. On the other hand, very limited products were detected after 14 h reaction when $Cu(CF_3SO_3)_2$ alone was employed as the catalyst (entry 5), indicating that $Cu(CF_3SO_3)_2$ alone is not catalytically active in furfural oxidation. However, when 0.02 mmol of $H_5PV_2Mo_{10}O_{40}$ and 0.02 mmol of $Cu(CF_3SO_3)_2$ were introduced as catalysts in this reaction, the total yields of 61.5% can be achieved including 54% of maleic anhydride and 7.5% of 5-acetoxyl-2(5H)-furanone (entry 6). When the concentration of $Cu(CF_3SO_3)_2$ increases from 0.02 mmol to 0.32 mmol (entries 6, 7, 8, 9) with a fixed loading (0.02 mmol) of $H_5PV_2Mo_{10}O_{40}$, the total yields of products decrease obviously from 61.5% to 24.5%, which can be rationalized by that, in addition to improve the catalytic efficiency, Cu(II) may also decompose both maleic acid and anhydride as disclosed above.

Mechanistic studies of furfural oxidation

It is well known that furfural is not very stable because of its polymerization when exposed to oxygen. The initial step of polyemerization is that the hydrogen atom at the 5-position of furfural is first abstracted by oxygen to generate a furfural radical which attacks the C=O bond of another furfural which initializes the polymerization[19]. Similarly, the maleic anhydride formation could be initialized from the same furfural radical intermediate (**1**) as well as in polymerization, and a plausible mechanism has been proposed in Scheme 1. After the first hydrogen atom being abstracted by either oxygen or $H_5PV_2Mo_{10}O_{40}$ to generate the furfural radical, which may initialize polymerization to form resins, or proceed with electron transfer to generate the furfural cation intermediate **2**. This cation intermediate **2** may next react with either H_2O or HOAc. If it is attacked by H_2O, the intermediate **3** is generated via pathway **I**, followed by 1,4-rearrangement to generate the intermediate **4**. The intermediate **4** further goes through decarbonylation and electron transfer to form the intermediate **5**. The decarbonylation has been indicated by the detection of CO with the online gas analyzer, which revealed a volume fraction of 0.80% for CO and 3.44% for CO_2 in the gas mixture after reaction. The intermediate **5** is next attacked by H_2O to form the intermediate **6** which is finally oxidized to maleic anhydride, the major product of this reaction. The formation of the key intermediate **6** has been identified by GC-MS. Possibly due to the poor stability under the catalytic conditions, other intermediates in pathway **I** were not detected. Alternatively, the intermediate **5** can also be attacked by HOAc to form 5-acetoxyl-2(5H)-furanone which represents 7.5% of products in analysis. Formation of maleic acid can be rationalized by hydration of maleic anhydride, because water is naturally generated in oxidation.

Alternatively, the intermediate **2** can also be attacked by HOAc to generate the intermediate **7** (see pathway **II**). Through similar decarbonylation and electron transfer, the intermediate **7** gives the intermediate **8**. In viewing of the structure of identified products, the intermediate **8** is more likely to react with H_2O rather than HOAc to produce the intermediate **9** which goes through 1,4-rearrangement to yield 5-acetoxyl-2(5H)-furanone, one identified product in this reaction. After hydrogen abstraction and electron transfer, 5-acetoxyl-2(5H)-furanone gives the intermediate **10** which reacts with water, followed by releasing of H^+ to form the intermediate **11**. The intermediate **11** can release HOAc to form maleic anhydride as the major product.

Unlike the pathway **I**, the product 5-acetoxyl-2(5H)-furanone is an intermediate for maleic anhydride formation in pathway **II**. To distinguish pathway **I** from pathway **II**, both of which has the identified compound **6** formation, 5-acetoxyl-2(5H)-furanone was employed as the substrate in place of furfural under the identical catalytic oxidations. However, the yield of maleic anhydride from 5-acetoxyl-2(5H)-furanone is only 0.7%. If it was true for maleic anhydride formation through pathway **II**, using either furfural or 5-acetoxyl-2(5H)-furanone as the starting material would generate similar yield of maleic anhydride. In another experiment, formation kinetics of both maleic anhydride and 5-acetoxyl-2(5H)-furanone revealed that 5-acetoxyl-2(5H)-furanone is not the intermediate for maleic anhydride formation, and clearly, they are generated in parallel (Figure 1). Thus, the trace formation of maleic anhydride from 5-acetoxyl-2(5H)-furanone as starting materials has clearly excluded pathway **II** for maleic anhydride formation. That is, attacking of the intermediate **2** by water is preferred over HOAc, which leads to the pathway **I**.



Scheme 1 Proposed mechanism for furfural oxidation catalyzed by $H_5PV_2Mo_{10}O_{40}$ and $Cu(CF_3SO_3)_2$

In oxidation of furfural to maleic anhydride, one carbon atom needs to be removed from the reactant. In literatures, furan was frequently proposed as the intermediates in vapor phase oxidation of furfural [8-12]. In this catalytic system, decarbonylation may also have chance to take place prior to other steps. Thus another plausible mechanism can happen as pathway **III** in Scheme 1. The hydrogen in the aldehyde functional group of furfural may be first abstracted by either oxygen or $H_5PV_2Mo_{10}O_{40}$, generating the intermediate **12**. After decarbonylation and electron transfer of the intermediate **12**, the intermediate **13** can be generated. Attacking on the intermediate **13** by H_2O forms the intermediate **14** which further goes through 1,4-rearrangement to yield 2(5H)-furanone. The formation of 2(5H)-furanone has been identified by GC-MS, but it does not exist as an intermediate in pathway **I** and **II**, thus supporting the existence of the pathway **III** in furfural oxidation. After hydrogen abstraction from 2(5H)-furanone by either oxygen or $H_5PV_2Mo_{10}O_{40}$, 2(5H)-furanone radical is generated, which further proceeds with electron transfer to form the intermediate **5**. Then, similar pathway may next happen as well as that in pathway **I** which provides maleic anhydride and 5-acetoxyl-2(5H)-furanone as the final products. However, in the experiment using 2(5H)-furfuran in place of furfural as pathway **III** may exist but just serve as a minor pathway. It is worth to note that, in the complimentary experiments using furan in place of furfural as substrate, it provides only 0.2% of maleic anhydride with mostly conversion of furan to resins. Particularly, there is no furan product detected in furfural oxidation here. Thereof, it could confirm that furan is not the intermediate in maleic anhydride formation for furfural oxidation in liquid phase, which is different from those vapor phase oxidations of furfural [7-12].

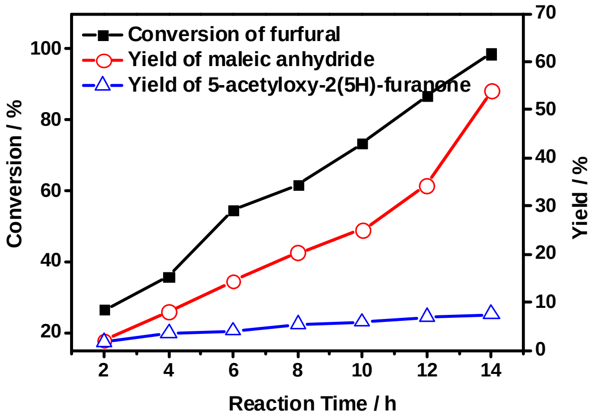


Figure 1. Catalytic kinetics of furfural oxidation with $H_5PV_2Mo_{10}O_{40}\cdot xH_2O$ plus $Cu(CF_3SO_3)_2$ catalyst. Conditions: $H_5PV_2Mo_{10}O_{40}\cdot xH_2O$, 0.02 mmol; $Cu(CF_3SO_3)_2$, 0.02 mmol; furfural, 2.4 mmol; CH_3CN, 2 mL; HOAc, 1.3 mL; O_2, 20 atm; temperature, 383 K.

Taken together, based on GC-MS identifications of the reaction intermediates and the final products, the kinetic analysis of 5-acetoxyl-2(5H)-furanone and maleic anhydride formations, and the control experiments using furan, 5-acetoxyl-2(5H)-furanone and 2(5H)-furfuran as starting materials, the dominant pathway for maleic anhydride and 5-acetoxyl-2(5H)-furanone formations could be signed to the pathway **I** with the pathway **III** as a minor one for 2(5H)-furanone formation.

Another notable fact is that adding Lewis acids may improve the maleic anhydride formation as demonstrated in Table 2, and particularly, adding copper(II) provides the highest total yields of three products. The promotion effects of Lewis acids in homogeneous oxidation have attracted much attention than ever, and it has been found that adding Lewis acids would greatly accelerate electron transfer reaction in both catalytic and stoichiometric oxidations[17,18]. The acceleration effects of Lewis acids in oxidations are generally attributed to their linkages to the redox metal ions which leads to the increase of their redox potentials, thus accelerates the electron transfer rate. As demonstrated in Scheme 1, the electron transfer steps are crucial for furfural oxidation to maleic anhydride. In pathway **I**, electron transfer from furfural radical (**1**) to generate furfural cation (**2**) is crucial for competing with furfural polymerization, while electron transfer after decarbonylation of the intermediate **4** is also essential for the formation of expected products. Since Lewis acids alone are inactive for maleic anhydride formation, the roles of added Lewis acids may be attributed to promote the electron transfer from these radical intermediates to $H_5PV_2Mo_{10}O_{40}$ catalyst.

In the experiment using $H_5PV_2Mo_{10}O_{40}$ catalyst alone, it still provide quantitative conversion of furfural with large amount of maleic anhydride formation, whereas the activity of copper(II) alone as catalyst was very poor, providing minor products (see Table 4). Thus, $H_5PV_2Mo_{10}O_{40}$ may independently function as hydrogen abstraction agent to initialize the reaction and serve other hydrogen abstractions as shown in Scheme1, while copper(II) ion does not. However, copper(II) has been well known as a trapper of organic radicals to generate organic cation intermediates[20], thus copper(II) is able to independently trap the furfural radical and the radical intermediate after decarbonylation. Accordingly, adding copper(II) to $H_5PV_2Mo_{10}O_{40}$ catalyst may further improve the total yield of three products. Furthermore, in another experiment, we also found that, as a redox metal ion, copper(II) can re-oxidize the reduced $H_5PV_2Mo_{10}O_{40}$ catalyst. That is, adding 2 equiv of $H_5PV_2Mo_{10}O_{40}$ to the ascorbic acid solution at room temperature, the catalyst remains its brick red color. Upon heating the solution, the color turns to blue in minutes, a typical color of reduced heteropolyacid. When adding 2 equiv of $Cu(CF_3SO_3)_2$ to the resulting heteropoly blue solution, the color turns back to brick red immediately, supporting that copper(II) can efficiently re-oxidize the reduced $H_5PV_2Mo_{10}O_{40}$ catalyst back to the active form, thus speeding up the catalytic rate. Thereof, copper(II) may play two roles in furfural oxidation, including trapping carbon radical by electron transfer and re-oxidizing the reduced heteropolyacid, which makes that adding copper(II) can provide the highest yields of expected products, while other Lewis acids may also improve the electron transfer ability of $H_5PV_2Mo_{10}O_{40}$, but generate less improvements than copper(II).

Experimental Section

All of the reagents are analytic purity grade, and used without further purification. $H_4PVMo_{11}O_{40}$, $H_5PV_2Mo_{10}O_{40}$ and $H_6PV_3Mo_9O_{40}$ catalysts were synthesized according to the literature [21]. Furfural was purchased from Shanghai Lingfeng Chemical Reagent Co., copper(II) trifluoromethanesulfonate ($Cu(CF_3SO_3)_2$) came from Alfa Aesar, sodium trifluoromethanesulfonate ($NaCF_3SO_3$), magnesium(II) trifluoromethanesulfonate ($Mg(CF_3SO_3)_2$), and scandium trifluoromethanesulfonate ($Sc(CF_3SO_3)_3$) were purchased from Aladdin, and other trifluoromethanesulfonates including $Ca(CF_3SO_3)_2$, $Al(CF_3SO_3)_3$, $Y(CF_3SO_3)_3$, and $Yb(CF_3SO_3)_3$ came from Shanghai Dibai Chemical Co. Manganese(II) acetate, palladium(II) acetate, iron(II) chloride, acetonitrile and acetic acid were purchased from local Sinopharm Chemical Reagent. The furfural oxidations were performed in stainless autoclaves, equipped with a magnetic stirring, a pressure gauge and automatic temperature control apparatus. The product identifications by GC-MS were performed on Agilent 7890A/5975C, and NMR analysis was performed on Bruker AV400.

Analytical methods

All of products were analyzed by HPLC and quantified using calibration curves generated with commercially available standards except 5-acetoxyl-2(5H)-furanone which was isolated and purified from catalytic solution. After a typical catalytic oxidation reaction, the product mixture was diluted with a known mass of the mobile phase, then filtered and analyzed by HPLC. The HPLC instrument is equipped with a UV detector and a CN column (250 mm × 4.6 mm), the mobile phase was iso-propanol with n-hexane (10%: 90%, v/v) containing acetic acid (0.1%) at 1 mL/min. The temperature of the column was 303 K.

General procedure for the furfural oxidation

In a typical experiment, $H_5PV_2Mo_{10}O_{40}\cdot xH_2O$ (34.8 mg, 0.02 mmol) and $Cu(CF_3SO_3)_2$ (7.4 mg, 0.02 mmol) were dissolved in 2 mL acetonitrile and 1.3 mL acetic acid in a glass tube, and furfural (231 mg, 2.4 mmol) was added into the solution. The glass tube was put into a 50 mL stainless autoclave; then the autoclave was charged with 20 atm of oxygen. The reaction solution was magnetically stirred at 383 K in oil bath for 14 h. After the reaction, the autoclave was cooled to room temperature and carefully depressurized to normal pressure. Yields of maleic anhydride and 5-acetoxyl-2(5H)-furanone, and conversion of furfural were quantitatively analyzed by HPLC. Because maleic acid can not be detected under the analytic conditions of maleic anhydride and 5-acetoxyl-2(5H)-furanone, its yield was determined by comparing the total yields of maleic anhydride before and after dehydration procedure with excess acetic anhydride as described below. This pretreatment has also been verified to be valid by using pure maleic acid in control experiment. Isolation and characterization of 5-acetoxyl-2(5H)-furanone are also described as follows.

Analytic procedure for maleic acid by dehydration

After 14 h catalytic reaction, the solution was cooled and depressurized, then the mixture was diluted with acetonitrile to a 5 mL volumetric flask. 2.5 mL of diluted solution was further transferred into to a 50 mL round-bottomed flask and 5 mL of acetic anhydride was added into the solution. The mixture was then heated to reflux for 2 h with stirring for dehydration. Through this procedure, the generated maleic acid can be completely converted to maleic anhydride which can be analyzed by HPLC method as described above. Particularly, the validity of this procedure has been verified by using pure maleic acid in control experiment.

Isolation and characterization of 5-acetoxyl-2(5H)furanone

After 14 h reaction of above described furfural oxidation, the autoclave was cooled to room temperature and depressurized to atmosphere pressure. The insoluble mass was filtered, and then acetonitrile was removed with rotary evaporator under vacuum. The resulting mixture was diluted with 2 mL water, and excess $NaHCO_3$ (2 g) were added to neutralize acetic acid and maleic anhydride. Next, the aqueous mixtures were extracted with dichloromethane (3×2 mL). The combined organic layers were concentrated under reduced pressure and the oily residue was further purified by silica gel chromatography with hexane/ethyl acetate 1:1 as eluent to obtain yellow oil as the product (0.18 mmol, 7.5% yield). ^1H NMR (300 MHz, $CDCl_3$, 25℃， TMS) $\delta = 2.14$ (s, CH_3), 6.29 (dd, J = 0.8 Hz, 1.6 Hz, CH), 6.96 (s, CH), 7.32 ppm (dd, J =1.2 Hz, 5.6 Hz, CH); ^{13}C NMR (75 MHz, $CDCl_3$, 25℃, TMS): $\delta = 20.58, 93.79, 125.13, 149.80, 168.88, 169.65$ ppm.

Control experiment using 5-acetoxyl-2(5H)-furanone as substrate

$H_5PV_2Mo_{10}O_{40}\cdot xH_2O$ (34.8 mg, 0.02 mmol) and $Cu(CF_3SO_3)_2$ (7.4 mg, 0.02 mmol) were dissolved in 2 mL acetonitrile and 1.3 mL acetic acid in a glass tube, and then 5-acetoxyl-2(5H)-furanone (341 mg, 2.4 mmol) was added to the solution. The glass tube was put into a 50 mL stainless autoclave. Then the autoclave was charged with 20 atm of oxygen. The reaction solution was magnetically stirred at 383 K in oil bath for 14 h. Next, similar analysis procedures were conducted as well as those for furfural oxidation.

Control experiment using 2(5H)-furanone as substrate

$H_5PV_2Mo_{10}O_{40}\cdot xH_2O$ (34.8 mg, 0.02 mmol) and $Cu(CF_3SO_3)_2$ (7.4 mg, 0.02 mmol) were dissolved in 2 mL acetonitrile and 1.3 mL acetic acid in a glass tube, and then 2(5H)-furanone (202 mg, 2.4 mmol) was added into the solution. The glass tube was put into a 50 mL stainless autoclave. Then the autoclave was charged with 20 atm of oxygen. The reaction solution was magnetically stirred at 383 K in oil bath for 14 h. Next, similar analysis procedures were conducted as well as those for furfural oxidation.

Control experiment using furan as substrate

$H_5PV_2Mo_{10}O_{40}\cdot xH_2O$ (34.8 mg, 0.02 mmol) and $Cu(CF_3SO_3)_2$ (7.4 mg, 0.02 mmol) were dissolved in 2 mL acetonitrile and 1.3 mL acetic acid in a glass tube, and then furan (163 mg, 2.4 mmol) was added to the solution. The glass tube was put into a 50 mL stainless autoclave. Then the autoclave was charged with 20 atm of oxygen. The reaction solution was magnetically stirred at 383 K in oil bath for 14 h. Next, similar analysis procedures were conducted as well as those for furfural oxidation.

Conclusions

A new oxidation method has been explored to catalytically convert renewable furfural to maleic anhydride using $H_5PV_2Mo_{10}O_{40}$ plus $Cu(CF_3SO_3)_2$ as catalysts in liquid phase. Notably, a highly valorized synthetic intermediate with biological importance, 5-acetoxyl-2(5H)-furfuran, has also be produced as a minor product. This method offers an alternative route to maleic anhydride synthesis which is not competitive with human being. Detailed mechanistic studies revealed that, in the dominant oxidation pathway, the reaction is initiated by hydrogen abstraction from the 5-position of furfural; next, maleic anhydride and 5-acetoxyl-2(5H)-furanone are formed in parallel. These results have provided novel insights to understand the oxidation mechanisms of furan sketch based biomass, thus benefits the design of the selective oxidation catalysts and control of their reactivity in biomass valorizations.

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Notes and references

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