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ARTICLE

Tungstosulfonic acid as an efficient solid acid catalyst for acylal synthesis for the protection of aldehydic carbonyl group

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Tungstosulfonic acid (TSA) has been found to be an efficient solid acid catalyst for the protection of aldehydic carbonyl groups by geminal diacetate (acylal) formation following nucleophilic addition of acetic anhydride under neat conditions as well as in solvent. The TSA catalyst is fully characterized by infrared spectroscopy, wide-angle X-ray scattering analysis, and scanning electron microscopy with energy dispersive X-ray spectroscopy. The deprotection of acylals to corresponding aldehydes has also investigated at the similar conditions. The catalyst can be reused seven times without significant loss of activity. In addition, no chromatographic separations are needed to obtain the desired products. This method is a green approach for the chemoselective protection of aldehydes in the presence of ketones.

1. Introduction

Heterogeneous solid acid (HSA) catalysts have a variety of advantages over liquid acid catalysts and have received extensive attention in synthetic organic chemistry as a result of their financial and environmental benefits, which include simple product separation, possible recycling, and reduced liberation of toxic residues into the atmosphere[1]. The ability to deploy HSA catalysts under neat experimental conditions is an important benefit in industrial chemistry. Sulfonic-acid-supported heterogeneous catalysts drive difficult organic transformations faster and employ mild reaction conditions. These catalysts enable feasible and cost-effective synthetic procedures. Because solid catalysts can be separated from reaction mixtures by simple filtration, they can be reused a number of times, which reduces the risk of discharging poisonous reaction residues into the environment compared with conventional homogeneous catalysts. In recent years there has been considerable research activity in the use of sulfonic-acid-supported catalysts in synthetic organic reactions. Sulfonic-acid-supported catalysts have attracted attention because of their many advantages, which include high thermal stability, low toxicity, high efficiency, good selectivity, low expense, reusability, and ease of separation of the catalyst from the reaction mixture[2,3]. Tungstosulfonic acid (TSA) is a class of heterogeneous acid catalyst and the chemical structures of tungstic acid (TA) and TSA are shown in Fig 1.

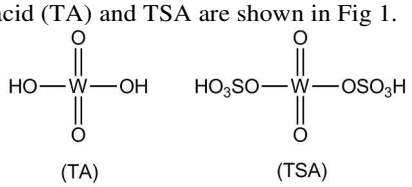


Fig 1. The chemical structures of TA and TSA.

Selective protection of aldehydic carbonyl groups by conversion to their corresponding acylals is an important component of multistep organic syntheses. A crucial property of the acylals formed in this process is their stability in neutral and basic media[4]. Reagents available for the protection of aldehydic carbonyl groups include ethanedithiol[5], alcohols[6], 2-mercaptoethanol[7], acetic anhydride[8], and trialkyl orthoformate[9]. Among all of them acetic anhydride is easy to handle and avoid the offensive odour. Typically, formation of acylals is promoted by strong protic acids such as NH_2SO_3H[10], KHSO4[11], and H_2SO_4[12,13]and Lewis acids such as $ZrCl_4$[14], $AlCl_3$[15], and $Bi(OTf)_3$[16]. From economic and environmental points of view use of heterogeneous catalysts such as $HClO_4.SiO_2$[17], MCM-41-SO_3H[18], and zeolite bet supported sulfonic acid (BEA-SO_3H)[19] also has been reported. However, Lewis acids are susceptible to moisture, and the other catalysts exhibit disadvantages that may include requirement of a long reaction time, high catalyst loading, high temperature, and microwave or ultrasound stimulation[10]. Therefore, the development of an economical protocol employing an easily accessible low toxicity solid acid catalyst and the ability to proceed under neat conditions is greatly preferred for the synthesis of acylals. Synthetic heterocyclic compounds are most important in the fields of organic and medicinal chemistry because of their broad range of pharmacological applications.

In various research laboratories and chemical industries enormous quantities of organic solvents are used and are wasted all over the world. The development of neat (solvent-free) conditions can play an increasingly vital role in synthetic organic chemistry, from not only a practical but also an ecological point of view[20]. The most significant goals of "green chemistry" include atom economy, prevention of waste, use of

renewable feedstock, use of catalytic reagents, reduction of expenses, easy workup and fast reaction rates[21]. Furthermore, the reduction of by products and the reduction of evaluated toxic gas during the reaction are also an important factor in green chemistry. The most important goals of neat chemistry are to reduce the use of toxic organic solvents, toxic reagents, and laborious work-up procedures associated with the synthesis of various organic compounds.[22–29]

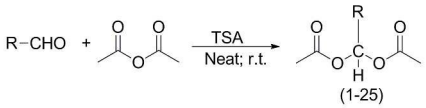
To the best of our knowledge in the open literature there have been no reports on the tungstosulfonic acid (TSA) catalysed synthesis of acylals. Considering this green chemistry in mind we report herein the use of TSA as a catalyst for the conversion of aldehydes to acylals using acetic anhydride as protecting agent, which is one of the efficient ways of protecting aldehyde group. The TSA catalysed reaction was found to be an environmentally benign, solvent-free, inexpensive, non-volatile and non-corrosive process. In addition the heterogeneous TSA catalyst was easy to prepare and recyclable.[30]

2. Results and discussion

In this work 25 acylals were synthesized by using the environmentally friendly TSA catalyst under neat conditions. Among them six compounds, **7**, **8**, **9**, **14**, **15** and **21**, are new compounds. The method offers many advantages over other literature procedures in terms of yield, ease of preparation, and recyclability of the catalyst. Moreover, we studied the deprotection of acylals under solvent-free conditions. The deprotection of acylals to their corresponding aldehydes proceeds in good yields in the presence of 2.5 mole% of TSA.

2.1. Chemistry

In general the protection of aldehydes is very important one during multistep synthesis. Furthermore, the protection of aldehydes by reaction with acetic anhydride is impossible to proceed without the use of a catalyst. Preparation of acylals usually requires high catalyst loadings, long reaction times, and exotic reagents to promote formation of the desired product. To avoid these problems we performed acylal formation reaction in the presence of TSA that is inexpensive, easily to prepare, and recyclable at mild and neat reaction conditions (Scheme 1).



(1-25)

Entry	R	Yield (%)	Entry	R	Yield (%)	Entry	R	Yield (%)
1	4-MePh	99	9	2Cl-6F-Ph	94	17	2OH-4-$(CH_3)_2$-N-Ph	0
2	4-NO_2Ph	97	10	2-ClPh	97	18	4-$(CH_3)_2$-N-Ph	0
3	Ph	96	11	2-BrPh	99	19	4-^{i}PrPh	95
4	4-OMePh	95	12	4-BrPh	98	20	An	97
5	3,5-OMePh	93	13	4-OHPh	93	21	Py	98
6	3,4,5-OMePh	95	14	2-OH-5BrPh	97	22	Ff	98
7	4-OEtPh	96	15	2-OH-3ClPh	96	23	5-MeFf	96
8	2F,4Br-Ph	97	16	2OH-3,5Cl-Ph	96	24	^{i}Pr	64
						25	n-C_5H_{13}	63

Ph= Phenyl, An= Anthracene, Py= Pyrene, Ff= Furfural

Scheme 1. Synthesis of a series of acylals (1–25).

As a first step we investigated acylal synthesis using several inexpensive and easily prepared solid-supported acid catalysts including silicatungstic acid (STA),[31] SiO_2•$B(OH)_2$,[32] $KHSO_4$•SiO_2,[33] and SiO_2•SO_3H[34] under neat conditions. The results are summarized in Table 1. All catalysts gave acceptable yields except STA. In addition, we attempted the reaction usingtungstic acid as catalyst, but no desired product formed after 24 h. The reaction was also carried out using $ClSO_3H$ as catalyst; however, the yield was low and separation of the catalyst from reaction mixture was difficult. Subsequently we thought that the low yields could be improved by combining TA and $ClSO_3H$ to form Tungstosulfonic acid, which could be applied to the synthesis of acylals and would be easily separated from the reaction mixture. Pleasantly, the reactions proceeded efficiently in high yields. The synergistic property of TSA resulted in good yields compared to those of TA or $ClSO_3H$ alone.

Table 1. Effect of various catalysts on the synthesis of compound **1** in neat condition[a]

Entry	Catalyst	Catalyst amount (mol%)	Time (h)	Yield(%)[b]
1	Catalyst free	-	24	nr[c]
2	STA[31]	7	2	35
3	SiO_2•$B(OH)_2$[32]	5	0.3	75
4	$KHSO_4$•SiO_2[33]	5	0.5	78
5	SiO_2•SO_3H[34]	5	0.6	88
6	TA	5	24	nr[c]
7	$ClSO_3H$	1	0.1	75
8	TSA	1	0.5	84
9	TSA	1.5	0.1	91
10	TSA	2	0.1	96
11	TSA	2.5	0.03	99
12	TSA	3	0.03	99

[a]Reaction conditions: *p*-methyl benzaldehyde = 1 mmol, acetic anhydride=1 mmol, and TSA = 2.5mol %.

[b]Isolated yield measured gravimetrically.

[c]No reaction.

To compare the effectiveness of neat versus solvent reaction conditions for synthesis of **1** was performed with TSA as catalyst in different solvents (Table 2). When the reaction was conducted in protic solvents such as isopropanol (IPA), acetic acid (AcOH), methanol (MeOH), ethanol (EtOH), or water (H_2O), the reaction proceeded slowly and provided reduced product yields (Table 2, entries 2-6). However, when aprotic solvents such as toluene, 1,4-dioxane, chloroform ($CHCl_3$), or dichloromethane (CH_2Cl_2) were used, the reaction proceeded faster and resulted in higher product yields (Table 2, entries 7–10).

To establish the optimum catalyst level of TSA the model reaction was carried out using 1, 1.5, 2, 2.5, and 3 mol% of neat TSA at room-temperature (r.t).The product yields were 86%, 91%, 96%, 99%, and 99%, respectively (Table 1, entries 8–12). Increasing the amount of catalyst beyond 2.5 mol% offered no further enhancement of the reaction.

Table 2. Effects of various solvents on the synthesis of compound **1**[a]

Entry	Solvent	Time (min)	Yield (%)
1	Solvent-free	2	99
2	IPA	40	62
3	AcOH	45	64
4	MeOH	56	50
5	EtOH	60	65
6	H_2O	75	60
7	Toluene	35	86
8	1,4-Dioxane	25	90
9	$CHCl_3$	23	89
10	CH_2Cl_2	18	91

[a]Reaction conditions: *p*-methyl benzaldehyde = 1 mmol, acetic anhydride =1 mmol, and TSA = 2.5 mol % at room temperature.

We next explored the general applicability of the reaction conditions employing a catalytic amount of TSA in the synthesis of acylals from various aromatic, heteroaromatic, and aliphatic aldehydes (Table 3). Results were obtained within 2–9 min. We found the reaction to be well-suited to compounds containing halide, nitro, cyano, methoxy, and ethoxy functionalities. In the case of hydroxy benzaldehyde and salicylaldehydes the corresponding triacetates were formed (**13–16**). It is possible to monitor the protection reaction of aldehydes with acetic anhydride visually. In case of aromatic aldehydes a clear solution is observed upon mixture of the aldehyde and anhydride; addition of the catalyst to the reaction mixture results in the formation of a solid (after stirring for a few minutes) indicating completion of the reaction. Exceptions to this rule are the 4-ethoxy-and 4-isopropyl-benzaldehyde derivatives (**7** and **19**), in which case liquids are obtained as indicated by thin layer chromatography (TLC). Aliphatic aldehydes (**24** and **25**) also formed liquids and were identified by TLC. In the case of *p*-dimethylamino salicylaldehyde and *p*-(*N*,*N*-dimethylamino)benzaldehyde) TSA was notable to catalyse conversion to the corresponding acylals (**17 and 18**).

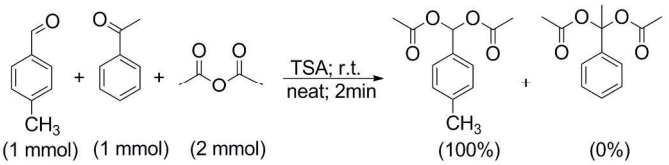
No reaction was observed for acetophenone at room temperature after 24 h as well as at 60 °C after 12 h. No new spot was observed by TLC, and no corresponding protons were observed in the NMR spectrum. Encouraged by this result, we conducted a competitive reaction involving acylation of *p*-methyl benzaldehyde in the presence of acetophenone under our standard reaction conditions. We found that *p*-methyl benzaldehyde was converted to the corresponding acylal, while acetophenone remained unreacted (Scheme 2).This examination indicates that aldehydes are more reactive than ketones most probably due to higher electrophilicity and less steric hindrance of aldehyde than ketone.

In addition to the synthetic process we investigated the possible deprotection of product acylals within the same catalytic system by adding water. For this purpose the reaction system was monitored for 2 h after forming acylal **1** from *p*-methyl benzaldehyde without changing conditions. Conversion of the reaction system from solid to oily liquid in water suggested that the product acylal is deportected (Scheme 3). The resulting mixture was examined by NMR spectroscopy

Table 3. Solvent-free TSA-catalyzed acetylation of various aldehydes with acetic anhydride at room temperature[a]

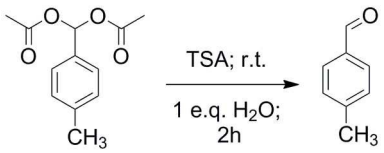
Entry	R in R–CHO	Yield (%)	Time (min)	m.p. (°C)
1	4-Me-C_6H_4	99	2	63-65
2	4-NO_2-C_6H_4	97	5	124-125
3	C_6H_5	96	4	43-44
4	4-OMe-C_6H_4	95	6	80-82
5	3,5-OMe-C_6H_3	93	8	93-95
6	3,4,5-OMe-C_6H_2	95	7	111-113
7	4-OEt-C_6H_4	96	5	Oil
8	2-F-4-Br-C_6H_3	97	5	50-52
9	2-Cl-6-F-C_6H_3	94	4	92-94
10	2-Cl-C_6H_4	97	3	56-57
11	2-Br-C_6H_4	99	2	78-79
12	4-Br-C_6H_4	98	3	81-82
13	4-OH-C_6H_4	93	8	93-94
14	2-OH-5-Br-C_6H_3	97	5	92-94
15	2-OH-3-Cl- C_6H_3	96	4	65-66
16	2-OH-3,5-Cl-C_6H_2	96	5	72-74
17	2-OH-4-$(CH_3)_2$-N-C_6H_3	0	10h	nr[c]
18	4-$(CH_3)_2$-N-C_6H_4	0	10h	nr[c]
19	4-^{i}Pr-C_6H_4	95	4	Oil
20	$C_{14}H_9$ (Anthrecene)	97	5	200-202
21	$C_{14}H_9$ (Pyrene)	98	3	66-68
22	2-Furfural(C_4H_3O)	98	6	51-52
23	5-Me-2-Furfural(C_4H_2O)	96	8	50-52
24	$CH(CH_3)_2$	64	8	Oil
25	C_5H_{13}	63	7	Oil

[a]Reaction conditions: *p*-methyl benzaldehyde =1 mmol and acetic anhydride =1mmol.



Scheme 2. Competitive acylal formation from *p*-methyl benzaldehyde in the presence of acetophenone.

without purification. A ^{1}H NMR spectrum of the resulting mixture before purification show a singlet at δ 9.91 ppm which is corresponding to an aldehydic proton. In addition there were no peaks between δ 80–95 ppm in the ^{13}C NMR spectrum, indicating the absence of Ar–CH carbon. The new peak around δ 178 ppm clearly indicates the carbonyl carbon. All of these results show that aceticanhydride is converted to acetic acid during the deprotection reaction (Fig. 2).



Scheme 3. TSA-catalyzed cleavage of acylal **1** to *p*-methyl benzaldehyde in the presence of water.

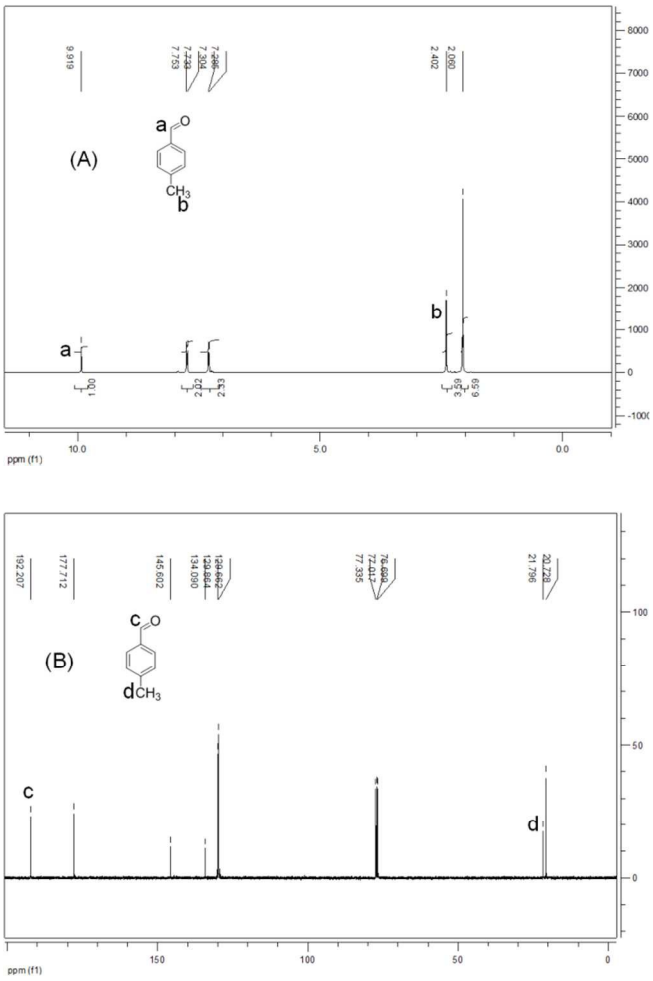


Fig. 2. (A) ^{1}H NMR and (B) ^{13}C NMR spectra of solution mixture after 2 h of reaction.

The performance of TSA compared to that of other recently reported heterogeneous catalysts for the acylation of aldehydes is summarized in Table 4.In 2013 Zareyee[35] reported the formation of acylals using a nanosilica material (SBA-15-Ph-PrSO_3H); the reaction rate was high, and acetic anhydride was used in excess. Tourani et al[18], reported the synthesis of acylals using MCM-41-SO_3H, wherein the heterogeneous catalyst loading was high; the product yield was low compared that of TSA. Kannasaniet al[36]., used $NaHSO_4$-SiO_2 as a supported catalyst at high loading with a fourfold excess of acetic anhydride; column chromatography was used for separation of the acylals. In 2007 Hajipour et al[37]., employed P_2O_5/Al_2O_3 as a catalyst for the protection of aldehydes with acetic anhydride; this procedure required a long time. Compared to all the heterogeneous acid catalysts mentioned above, TSA as described herein is superior for the high yield synthesis of acylals, because it requires neither harsh reaction conditions, additional energy input (i.e., microwave or ultra-sonication), nor laborious work-up procedures.

Table 4. Comparison of various catalysts used for the synthesis of acylal **1**[a]

Entry	Catalyst (mg)	Solvent	Time (min)	Yield (%)	Ref.
1	SBA-15Ph-pr-SO_3H (1)	Neat	5	100	31
2	MCM-41-SO_3H (10)	Neat	3	95	18
3	$NaHSO_4$-SiO_2 (25%/wt)	Neat	15	94	32
4	P_2O_5/Al_2O_3 (15 mol%)	Neat	45	86	33
5	TSA (2.5 mol%)	Neat	2	99	This work

[a]Reaction conditions: *p*-methyl benzaldehyde = 1 mmol and acetic anhydride =1mmol.

Reusability of a catalyst is crucial for large-scale operations and from an industrial point of view. Therefore, the reusability of TSA was examined in the synthesis of **1** formed by reaction of acetic anhydride with *p*-methyl benzaldehyde. The catalyst was effortlessly recovered by adding chloroform to the reaction mixture. Insoluble TSA was separated by simple filtration, washed twice with chloroform (20 mL), and dried under vacuum at 100 °C. The catalyst displayed good reusability after 7 runs (Fig.3).

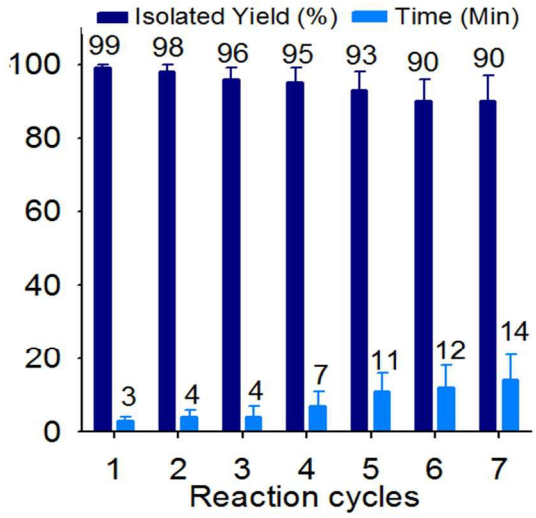
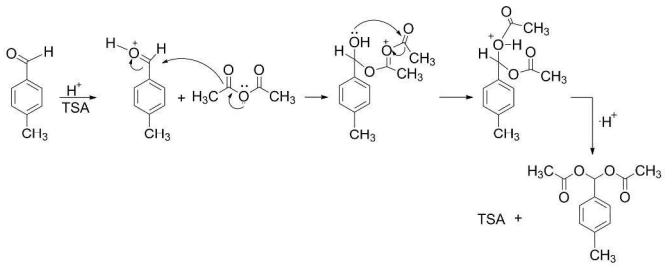


Fig. 3. Effect of recycling of TSA on the yield of acylal **1**.

Based on the obtained results, the reaction mechanism might be proposed for protection of aldehydes with acetic anhydride in the presence of TSA (Scheme 4). At first the *p*-methyl benzaldehyde reacts with acidic hydrogen from TSA to form an intermediate benzylideneoxonium ion which reacts with acetic anhydride to form an oxonium ion. This oxonium ion undergoes an intramolecular rearrangement and the proton is rearranged to TSA to form targeted acylals.



Scheme 4. The plausible reaction mechanism for the formation of acylals in presence of TSA.

The structures of all the compounds were confirmed by IR, ^{1}H and ^{13}C NMR spectroscopies. The IR spectra of compounds **1–25** showed the expected regions. In the ^{1}H NMR spectrum, the Ar-CH proton signal appeared as a singlet in the region of δ 9.22–7.56 ppm. The remaining proton signals were observed in the expected regions. In the ^{13}C NMR spectra, the Ar-CH carbon signal appeared at δ 89.5–83.6 ppm confirms the formation of acylals and all known products were identical with those reported in the literature[31].The detailed descriptions of the spectral data for all compounds (**1–25**) are given in the experimental section.

3. Conclusions

A straightforward, effective and green procedure for the synthesis of acylals catalysed by heterogeneous tungstosulfonic solid acid under neat conditions has been described. This low-cost method has a number of advantages including use of readily available chemicals, high yields, neat reaction conditions (solvent-free), and easy work-up procedures. The procedure provides chemists with a fast and effective method for preparing diversely substituted acylals. The TSA catalyst has been fully characterized by FTIR, XRD, and SEM-EDX to confirm the sulfonation of tungstic acid.

4. Experimental

4.1. General

The various substituted aldehydes were purchased from Sigma Aldrich Co. (St. Louis, MO, USA), tungstic acid (TA) and chloro sulfonic acid (Yakuri Pure Chemical Co., Japan).All experiments were carried out under solvent-free conditions. Analytical thin layer chromatography (TLC) was carried out at ethyl acetate/n-hexane (8/2) mixture on pre-coated silica gel plates (Merck Chem., Germany) and developed by use of iodine. Fourier transform infrared (FT-IR) spectra were recorded on a Shimadzu IR Prestige 21 spectrometer at room temperature. The samples were analyzed as KBr discs in the range 3500–500 cm^{-1}. ^{1}H NMR (400 MHz) and ^{13}C NMR (100 MHz) spectra were recorded on a Varian INOVA 400 NMR spectrometer at room temperature. Chemical shift values are reported relative to tetramethylsilane (TMS, Me4Si). The data are presented as follows: chemical shift (ppm), multiplicity (s = singlet, d = doublet, m = multiplet), and coupling constant, *J*(Hz). The XRD analysis was performed by use of an automatic Philips powder diffractometer with nickel-filtered Cu Kα radiation. The diffraction pattern was collected in the 2θ range of 0–80^{o} in steps of 0.02^{o} with counting times of 2s•step^{-1}. The microstructures of the samples and energy dispersive x-ray spectra (EDX) were investigated by use of an S-3000 scanning electron microscope (SEM; Hitachi, Japan).

4.2. General procedure for the synthesis of acylals 1–25.

In a 50-mL round bottom flask TSA (2.5 mol %) was added to a mixture of *p*-methyl benzaldehyde (1 mmol) and acetic anhydride (1 mmol). The reaction mixture was stirred at room temperature becoming solid within 2 min. Chloroform was added, and the insoluble catalyst was separated by simple filtration, washed twice with chloroform, and dried at 100 °C for 2h for reuse. The chloroform filtrate was evaporated under reduced pressure and the solid obtained was washed with petroleum ether (20 mL) three times. Recrystallization from dichloromethane afforded the resulting acylal, **1**. All known products afforded spectral and physical data consistent with those reported in the literature. New products were characterized by their IR, ^{1}H NMR, and ^{13}C NMR spectra. Detailed descriptions for all these compounds are given below.

4.3. Spectral characterization

4.3.1. *p*-Tolylmethylenediacetate(1). 99% yield in 2 min reaction time; solid; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.64 (s, 1H, Ar–CH), 7.39 (d, *J*=7.99 Hz, 2H, Ar–H) 7.19 (d, *J*=7.99 Hz, 2H, Ar–H), 2.35 (s, 3H, –CH_3), 2.09 (s, 6H, –CH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.7, 139.7, 132.6, 129.8, 126.5, 89.8, 21.3, 20.8; FTIR (KBr): ν=3428, 1678, 1575, 1418,1319, 754 cm^{-1}.

4.3.2. (4-Nitrophenyl)methylenediacetate (2). 97% yield in 5 min reaction time; solid; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 8.24 (d, *J*=8.78 Hz, 2H, Ar–H),7.70 (s, 1H, Ar–CH), 7.67 (d, *J*=8. 84 Hz, 2H, Ar–H), 2.13 (s, 6H, –CH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.5, 148.6, 141.8, 127.8, 123.8, 88.3, 20.7; FTIR (KBr): *v*= 3495, 3124, 1762, 1529, 1431, 1251, 856 cm^{-1}.

4.3.3. Phenylmethylenediacetate (3). 96% yield in 4 min reaction time; solid; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.66 (s, 1H, Ar–CH), 7.48–7.32 (m, 5H, Ar–H), 2.02 (s, 6H, –CH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.6, 135.5, 129.6, 128.5, 126.6, 89.6, 20.6; FTIR (KBr): *v*=3434, 1690, 1590, 1438, 1046 cm^{-1}.

4.3.4. (4-Methoxyphenyl)methylenediacetate (4). 95% yield in 8 min reaction time; solid; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.61 (s, 1H, Ar–CH), 7.44 (d, *J*=8.73 Hz, 2H, Ar–H), 6.90 (d, *J*=8.84 Hz, 2H, Ar–H), 3.80 (s, 3H, –OCH_3), 2.09 (s, 6H, –CH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.7, 160.6, 131.9, 128.2, 113.9, 89.7, 55.3, 20.9; FTIR (KBr): ν=3431, 3099, 1703, 1405, 1250 cm^{-1}.

4.3.5. (3,5-Dimethoxyphenyl)methylenediacetate (5). 93% yield in 8 min reaction time; solid; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.58 (s, 1H, Ar–CH), 6.64 (d, *J*=2.32 Hz, 2H, Ar–H), 6.46 (t, *J*=2.31 Hz, 1H, Ar–H), 3.78 (s, 6H,–OCH_3)

2.10 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.8, 160.9, 137.5, 107.1, 104.6, 101.6, 89.4, 55.4, 20.8; FTIR (KBr): ν=3428, 2975, 1678, 1575, 1319, 754 cm^{-1}.

4.3.6. (3,4,5-Trimethoxyphenyl)methylenediacetate (6). 95% yield in 7 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.57 (s, 1H, Ar–CH), 6.73 (s, 2H, Ar–H), 3.86 (s, 9H,–$(OCH_3)_3$), 2.11 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.7, 153.3, 139.0, 130.8, 103.8, 89.7, 60.7, 56.1, 20.8; FTIR (KBr): ν= 3435, 2941, 1687, 1587, 1330 cm^{-1}.

4.3.7. (4-Ethoxyphenyl)methylenediacetate (7). 96% yield in 5 min reaction time; Liquid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.59 (s, 1H, Ar–CH), 7.41 (d, *J*=8.8 Hz, 2H, Ar–H), 6.88 (d, *J*=8.8 Hz, 2H, Ar–H), 4.13–3.97 (m, 2H, $–OCH_2$), 2.08 (s, 6H, $–CH_3$), 1.39 (t, *J*=7.0 Hz, 3H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.8, 159.9, 128.0, 127.5, 114.4, 89.7, 63.5, 20.8, 14.7; FTIR (neat): ν= 3369, 2982, 1678, 1312, 1042 cm^{-1}.

4.3.8. (4-Bromo-2-fluorophenyl)methylenediacetate (8). 97% yield in 5 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.81 (s, 1H, Ar–CH), 7.40–7.26 (m, 3H, Ar–H), 2.10 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.2, 161.2, 129.2, 127.6, 124.3, 122.3, 119.5, 85.0, 20.6; FTIR (KBr): ν= 3462, 1762, 1604, 1373, 1127, 772, 632 cm^{-1}.

4.3.9. (4-Chloro-6-fluorophenyl)methylenediacetate (9). 94% yield in 4 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 8.09 (s, 1H, Ar–CH), 7.29–6.99 (m, 3H, Ar–H), 2.10 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.5, 162.9, 134.5, 131.5, 125.9, 121.3, 115.1, 86.0, 20.6; FTIR (KBr): ν= 3434, 2988,1690, 1408, 1315, 1046, 814, 714 cm^{-1}.

4.3.10. (2-Chlorophenyl)methylenediacetate (10). 97% yield in 3 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.96 (s, 1H, Ar–CH), 7.56–7.30 (m, 4H, Ar–H), 2.13 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.3, 133.2, 130.8, 129.9, 127.6, 126.9, 87.1, 20.7; FTIR (KBr): ν= 3434, 2968, 16901409, , 1267, 744, 558 cm^{-1}.

4.3.11. (2-Bromophenyl)methylenediacetate (11). 99% yield in 2 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.89 (s, 1H, Ar–CH), 7.58–7.52 (m, 2H, Ar–H), 7.37–7.33 (m, 1H, Ar–H), 7.27–7.23 (m, 1H, Ar–H), 2.13 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.3, 134.8, 133.1, 131.0,127.8, 127.5, 122.5, 89.1, 20.7; FTIR (KBr): ν= 3477, 3053, 1759, 1373, 687, 553 cm^{-1}.

4.3.12. (4-Bromophenyl)methylenediacetate (12). 98% yield in 3 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.60 (s, 1H, Ar–CH), 7.52 (d, *J*=8.55 Hz, 2H, Ar–H), 7.37 (d, *J*=8.23 Hz, 2H, Ar–H), 2.10 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, CDCl3): δ (ppm) 168.6, 134.5, 131.8, 128.4, 123.9, 89.1, 20.8; FTIR (KBr): ν=3473, 3093, 1756, 1690, 1372, 756, 601 cm^{-1}.

4.3.13. (4-Hydroxyphenyl)methylenediacetate (13). 93% yield in 8 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.65 (s, 1H, Ar–CH), 7.51 (d, *J*=8.68 Hz, 2H, Ar–H), 7.10 (d, *J*=8.58 Hz, 2H, Ar–H), 2.28 (s, 3H, $–CH_3$), 2.1 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 169.2, 168.6, 151.5, 133.1, 128.0, 121.8,89.2, 21.1, 20.8; FTIR (KBr): ν= 3253, 2829, 1673, 1446, 1384, 835, 605 cm^{-1}.

4.3.14. (5-Bromo-2-hydroxyphenyl)methylenediacetate (14). 97% yield in 5 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.83 (s, 1H, Ar–CH), 7.68 (d, *J*=8.8 Hz, 1H, Ar–H) 7.52–7.39 (m, 1H, Ar–H) 7.09 (d, *J*=8.8 Hz, 1H, Ar–H), 2.29 (s, 3H, $–CH_3$), 2.06 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.5, 168.0, 146.5, 133.4, 130.5, 128.7, 123.7, 109.2, 84.5, 20.8, 20.5; FTIR (KBr): ν=2242, 1825, 1648, 1356, 1152 cm^{-1}.

4.3.15. (3-Chloro-2-hydroxyphenyl)methylenediacetate (15). 96% yield in 4 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.83 (s, 1H, Ar–CH), 7.53–7.46 (m, 3H, Ar–H), 2.36 (s, 3H,–CH_3), 2.08 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.2, 145.1, 131.4, 130.3, 128.2, 126.9, 126.2, 85.2, 20.6, 20.3; FTIR (KBr): ν=3473, 2999, 1748, 1487, 1219, 755 cm^{-1}.

4.3.16. (3,5-Dichloro-2-hydroxyphenyl)methylenediacetate (16). 96% yield in 5 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.79 (s, 1H, Ar–CH), 7.50 (d, *J*=2.4 Hz, 1H, Ar–H),7.47 (d, *J*=2.4 Hz, 1H, Ar–H), 2.35 (s, 3H,–CH_3), 2.09 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.0, 143.7, 132.1, 131.4, 131.1, 129.1, 126.4, 109.9, 84.3, 20.6, 20.2; FTIR (KBr): ν=3431, 2875, 1672, 1274, 829,700 cm^{-1}.

4.3.17. (4-(Dimethylamino)-2-hydroxyphenyl)methylene-diacetate (17)[a]. [a]corresponding acylals not formed

4.3.18. (4-(Dimethylamino)phenyl)methylenediacetate (18)[a]. [a]corresponding acylals not formed

4.3.19. (4-(Isopropyl phenyl)methylenediacetate (19). 95% yield in 4 min reaction time; Liquid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.80 (s, 1H, Ar–CH), 7.40 (d, *J*=7.4 Hz, 2H, Ar–H), 7.37 (d, *J*=7.4 Hz, 2H, Ar–H), 3.19-2.98 (m, 1H,–CH), 2.09 (s, 6H, $–CH_3$), 1.75 (d, *J*=6.4 Hz, 6H,–CH_3),,); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.4, 148.2, 127.1, 122.4, 85.2, 32.4, 21.5, 20.2; FTIR (neat): ν=2342, 1785, 1648, 1136, 1032 cm^{-1}.

4.3.20. Anthrene-9-ylmethylenediacetate (20). 97% yield in 5 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 9.22 (s, 1H, Ar–CH), 8.68 (d, *J*=8.9 Hz, 2H, Ar–H), 8.51 (s, 1H, Ar–H), 8.01 (d, *J*=8.9 Hz, 2H, Ar–H), 7.60–7.46 (m, 4H, Ar–H), 2.10 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.9, 131.3, 130.5, 129.9, 128.9, 126.6, 125.6, 125.3, 125.0, 87.4, 20.8; FTIR (KBr): ν= 3462, 1762, 1373, 1245, 942, 590 cm^{-1}.

4.3.21. Pyren-1-ylmethylenediacetate (21). 98% yield in 3 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 8.56 (s, 1H, Ar–CH), 8.54–8.00 (m, 9H, Ar–H), 2.16 (s, 6H, $–CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.8, 132.4, 131.1, 130.4, 128.6, 128.5, 128.3, 128.0, 127.1, 126.1, 125.7, 125.6, 125.2, 124.8, 124.5, 122.9, 89.5, 20.9, 89.5, 20.9; FTIR (KBr): ν=3431, 3036, 1675, 1373, 834, 709 cm^{-1}.

4.3.22. Furan-2ylmethylenediacetate (22). 98% yield in 6 min reaction time; solid; ^1H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.69 (s, 1H, Ar–CH), 7.43 (t, *J*=0.8 Hz, 1H, Ar–H), 6.49 (d, *J*=1.2 Hz, 1H, Ar–H), 6.37–6.36 (m, 1H, Ar–H), 2.10 (s, 6H, $–CH_3$);

^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.4, 147.8, 143.6, 110.3, 109.7, 83.5, 20.7; FTIR (KBr): ν=3347, 3129, 2213, 1723, 1029, 800, 681 cm^{-1}.

4.3.23. (5-Methylfuran-2yl)methylenediacetate (23). 96% yield in 8 min reaction time; solid; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 7.582 (s, 1H, Ar–CH), 7.09 (d, *J*=3.6 Hz, 1H, Ar–H), 6.42 (d, *J*=3.2 Hz, 1H, Ar–H), 2.32 (s, 3H,–CH_3) 2.08 (s, 6H, –CH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ (ppm) 168.6, 152.2, 144.8, 110.2, 107.3, 83.8, 20.1, 14.2; FTIR (KBr): ν=3089, 1644, 1482, 1341, 685 cm^{-1}.

4.3.24. 2-Methylpropane-1,1-diyl diacetate (24). 64% yield in 8 min reaction time; Liquid; ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) 6.62 (d, *J*=5.6 Hz, 1H,–CH), 2.09 (s, 6H,–CH_3), 1.19 (m, 1H, –CH), 0.72 (d, *J*=8.6Hz, 6H,–CH_3); FTIR (neat): ν=2862, 1465, 1392, 1241, 725 cm^{-1}.

4.3.25. Hexane-1,1-diyl diacetate (25). 63% yield in 7 min reaction time; Liquid; ^{1}H NMR (400 MHz, $CDCl_3$): δ(ppm) 6.11 (t, *J*=5.6Hz 1H, –CH), 2.08 (s, 6H, –CH_3), 1.89-1.09 (m, 8H,$(CH_2)_4$), 0.79 (t, *J*=6.2 Hz, 3H, –CH_3); FTIR (neat): ν= 2874, 1826, 1452, 1261,1245, 1120, 676 cm^{-1}.

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Notes and references

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1. M. Parveen, F. Ahmad, A. M. Malla, S. Azaz, *New J. Chem.,* 2015, **39**, 2028–2041.
2. R. M. N. Kalla, H. Park, T. T .K. Hoang, I. Kim, *Tetrahedron Lett.,* 2014, **55**, 5373–5376.
3. A.R. Kiasat, A. Mouradzadegun, S. J. Saghanezhad, *J. Serb. Chem. Soc.,* 2013,**78**, 469–476.
4. T.W. Greene, P.G.M. Wuts, Protective Groups in Organic Synthesis, 3rd ed., John Wiley and Sons, New York, 1999.
5. G. Perin, L. G. Mello, C. S. Radatz, L. Savegnago, D. Alves, R. G. Jacob, E. J. Lenardao, *Tetrahedron Lett.,* 2010, **51**, 4354–4356.
6. S. Madabhushi, K. K. R. Mallu, N. Chinthala, C. R. Beeram, V. S. Vangipuram, *Tetrahedron Lett.,* 2012, **53**, 697–701.
7. F. Shirini, P. Sadeghzadeh, M. Abedini, *Chin. Chem. Lett.,* 2009, **20**, 1457–1460.
8. N. G. Khaligh, F. Shirini, *J. Mol. Catal. A: Chem.,* 2011, **348**, 20–29.
9. A. Roy, M. Rahman, S. Das, D. Kundu, S. K. Kundu, A. Majee, A. Hajra, *Synth. Commun.,* 2009, **39**, 590–595.
10. T. S. Jin, G. Sun, Y. W. Li, T. S. Li, *Green Chem.,* 2002, **4**, 255–256.
11. M. M. Heravi, K. Bakhtiari, S. Taheri, H. A. Oskooie, *Green Chem.,* 2005, **7**, 867–869.
12. M. J. Gregory, *J. Chem. Soc. B.,* 1970, 1201–1207.
13. M. Tomita, T. Kikuchi, K. Bessho, T. Hori, Y. Inubushi, *Chem. Pharm. Bull.,* 1963, **11**, 1484–1489.
14. G. Smitha, Ch. S. Reddy, *Tetrahedron,* 2003, **59**, 9571–9576.
15. S. Gowravaram, S. Abraham, T. Ramalingam, J. S. Yadav, *J. Chem. Res.,* 2002, **3**, 144–147.
16. M. D. Carrigan, K. J. Eash, M. C. Oswald, R. S. Mohan, *Tetrahedron Lett.,* 2001, **42**, 8133–8135.
17. V. T. Kamble, V. S. Jamode, N. S. Joshi, A. V. Biradara, R. Y. Deshmukha, *Tetrahedron Lett.,* 2006, **47**, 5573–5576.
18. H. Tourani, M. R. N. Jamal, M. G. Dekamin, M. Amirnejad, *C. R. Chimie,* 2012, **15**, 1072–1076.
19. R. J. Kalbasi, A. R. Massah, A. Shafiei, *J. Mol. Catal. A: Chem.,* 2011, **335**, 51–59.
20. D. J. C. Constable, P. J. Dunn, J. D. Hayler, G. R. Humphrey, J. L. LeazerJr, R. J. Linderman, K. Lorenz, J. Manley, B. A. Pearlman, A. Wells, *Green Chem.,* 2007, **9**, 411–420.
21. K. Tanaka, F. Toda, *Chem. Rev.,* 2000, **100**, 1025–1074.
22. R. M. N. Kalla, J. V. John, H. Park, I. Kim, *Catal. Commun.,* 2014, **57**, 55–59.
23. R. M. N. Kalla, M. R. Kim, I. Kim, *Tetrahedron Lett.,* 2015, **56**, 717–720.
24. R. M. N. Kalla, H. R. Lee, J. Cao, J. W. Yoo, I. Kim, *New J. Chem.,* 2015, **39**, 3916–3922.
25. R. M. N. Kalla, S. J. Byeon, M. S. Heo, I. Kim, *Tetrahedron,* 2013, **69**, 10544–10551.
26. R. M. N. Kalla, J. S. Choi , J. W. Yoo b, S. J. Byeon, M. S. Heo, I. Kim, *Eur. J. Med. Chem.,* 2014, **76**, 61–66.
27. K. R. M. Naidu, B. Satheesh Krishna, M.A. Kumar, P. Arulselvan, S. K. Ibrahim, O. Lasekan, *Molecules,* 2012, **17**, 7543-7555.
28. K. R.M. Naidu, S.I. Khalivulla, S. Rasheed, S. Fakurazi, P. Arulselvan, O. Lasekan, F. Abas, *Int. J. Mol. Sci.,*2013, **14**, 1843-1853.
29. K. R. M. Naidu, S. I. Khalivulla, P.C.R. Kumar, O. Lasekan, *Org. Commun.,* 2012,**5**, 150-159.
30. S. Khodabakhshi, B. Karami, *Tetrahedron Lett.,* 2014, **55**, 7136–7139.
31. B. Karami, V. Ghashghaee, S. Khodabakhshi, *Catal. Commun.,* 2012, **20**, 71–75.
32. M. Parveen, F. Ahmad, A. M. Malla and S. Azaz, *New J. Chem.,* 2015, **39**, 2028–2041.
33. A. Goswami, R. N. Das, N. Borthakur, *Indian J. Chem., Sect B.,* 2007, **46B,** 1893-1895.
34. M. A. Zolfigol, *Tetrahedron.,* 2001, **57**, 9509-9511
35. D. Zareyeea, S. M. Moosavi, A. Alaminezhad, *J. Mol. Catal. A: Chem.,* 2013, **378**, 227– 231.
36. R. K. Kannasani, V. V. S. Peruri, S. R. Battula, *Chem. Cent. J.,* 2012, **6**, 136–139.
37. A. R. Hajipour, A. Zareib, A.E. Ruohoa, *Tetrahedron Lett.,* 2007, **48**, 2881–2884.

Tungstosulfonic acid as an efficient solid acid catalyst for acylal synthesis for the protection of aldehydic carbonyl group

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Aldehydic carbonyl groups are eco-friendly protected by acetic anhydride using tungstosulfonic acid catalyst and the deprotection is successful at the similar conditions in presence of water.