Solvent free synthesis of acetyl salicylic acid over nano-crystalline sulfated zirconia solid acid catalyst

Beena Tyagi [**,1], Manish Kumar Mishra [1], Raksh Vir Jasra [*]

Discipline of Inorganic Materials & Catalysis, Central Salt & Marine Chemicals Research Institute (CSMCRI),
Council of Scientific and Industrial Research (CSIR), GB Marg, Bhavnagar-364 002, Gujarat, India

ARTICLE INFO

ABSTRACT

Acetyl salicylic acid, commonly known as Aspirin or Ecotrin, has been synthesized by an eco-friendly route using solid acid catalysts namely nano-crystalline sulfated zirconia, sulfated titania, zeolite H-beta, H-Y, H-ZSM-5 and acid treated K-10 clay. Among all the solid acid catalysts studied, nano-crystalline sulfated zirconia showed highest catalytic activity and was found to be efficient in minimal amount to obtain excellent yield (95 wt%) of acetyl salicylic acid crystals. Thermally regenerated catalyst showed similar yield as obtained with the fresh catalyst.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Solid acids have emerged as potential alternate catalysts to the conventional liquid acids [1,2] due to their non-hazardous nature, requirements in catalytic amounts, enhanced selectivity and easier post-reaction work-up. The ease of separation without resulting into problem of waste disposal and option of re-use of the solid acid catalysts render the processes employing solid acid catalysts as green processes. Among the various solid acid catalysts, sulfated zirconia is a potential catalyst for the isomerization of *n*-butane at ambient temperature [3] and has been extensively studied for the isomerization of *n*-alkanes, cycloalkanes and alkenes [4–7]. It has also been used for various acid catalyzed reactions such as alkylation, acylation, esterification, etherification, nitration, and oligomerization [8,9]. Besides sulfated zirconia, zeolites and acid treated clays are well known catalysts for acid catalyzed reactions. For example, we have reported excellent catalytic activity and selectivity for the desired product by using these solid acid catalysts for various industrially important organic transformations, such as isomerization of terpenes [10–13] and coumarin synthesis by Pechmann reaction [14,15] using sulfated zirconia; nitration of o-xylene

[16] and acylation of toluene [17] using zeolites; and isomerization of α-pinene [18] using acid treated clay. In the present study, we extended our focus to synthesize acetyl salicylic acid (ASA) using these solid acid catalysts via O-acetylation of salicylic acid with acetic anhydride.

Acetyl salicylic acid, commonly known by its trade name, Aspirin, is an effective non-steroidal analgesic, antipyretic and anti-inflammatory drug and is one of the most widely used medicines around the world. The use of aspirin extends beyond pain relief by inhibiting the production of prostaglandins chemicals responsible for inflammations to life saver by reducing the risk of heart stroke as it prevents the aggregation of platelets. Today more than 10 million kilograms of aspirin is annually produced world-wide and is the most successful product for drug industry that generates largest revenues for pharmaceutical companies.

Commercially, salicylic acid synthesized by Kolbe-Schmidt reaction [19] is acetylated with acetic anhydride in presence of an acid catalyst [20] mainly H_2SO_4 [21] and H_3PO_4 [22] at 80–90 °C. Pure acetyl salicylic acid is obtained after crystallization of cooled reaction mixture. The use of H_2SO_4 and H_3PO_4 is not desirable as these are corrosive, hazardous, not separable, not re-usable resulting to the problem of spent acid disposal. A brown liquid impurity also appears during re-crystallization of acetyl salicylic acid from water, usually in trace amount but sometimes in large quantity also, which is to be removed by filtering the hot aqueous solution and thus making process tedious and results into acetyl salicylic acid crystals of low purity.

Very few studies have been reported to synthesize acetyl salicylic acid to replace conventional H_2SO_4 [23–25]. Acetyl

* Corresponding author. Present address: R & D Centre, Reliance Industries Limited, Vadodara Manufacturing Division, Vadodara-391346, Gujarat, India.
Tel.: +91 265 6603935; fax: +91 265 6693934.
** Corresponding author.
E-mail addresses: btyagi@csmcri.org (B. Tyagi), rakshvir.jasra@ril.com (R.V. Jasra).
[1] Tel.: +91 278 567760; fax: +91 278 566970.
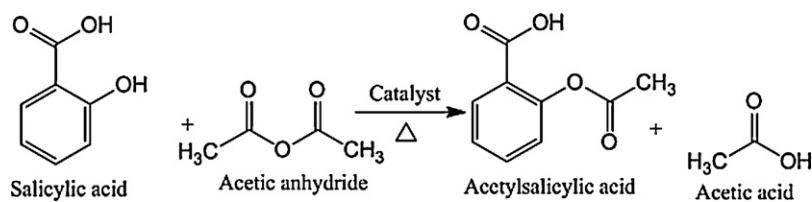
Scheme 1. Synthesis of acetyl salicylic acid by O-acetylation of salicylic acid with acetic anhydride over solid acid catalyst.

chloride-pyridine has been used [23,24] as the acetylating agent at lower temperature with 33% yield of acetyl salicylic acid. Peng and Song [25] reported water soluble 12-tungustophosphoric acid as a catalyst at room temperature with 57–71% yield of acetyl salicylic acid accompanied with the formation of a gummy polymeric by-product, which needs to be removed and thereby leading to an extra step in the process. Microwave assisted synthesis of acetyl salicylic acid from salicylic acid and acetic anhydride using H_3PO_4 [26–28] and other acidic as well as basic catalysts namely H_2SO_4, $AlCl_3$, $MgBr_2 \cdot OEt_2$, $CaCO_3$, NaOAc, NEt_3 and dimethylaminopyridine [29] is also reported. Besides being corrosive in nature, use of acid catalyst resulted into unwanted polymeric side-products. Use of base catalysts necessitates post reaction the neutralization of reaction mixture.

In the present study, we report the synthesis of acetyl salicylic acid by the O-acetylation of salicylic acid with acetic anhydride using nano-crystalline sulfated zirconia (Scheme 1). For comparison, other solid acid catalysts namely, sulfated titania, zeolite H-beta, H-Y, H-ZSM-5 and acid treated K-10 clay were also studied. The significance of the study lies in the solvent free economical synthesis of acetyl salicylic acid of high purity crystals in excellent yield (65–95 wt%) and the re-usability of the solid acid catalyst after separation followed by thermal activation. To the best of our knowledge, it is the first report [30] of the solvent free green catalytic synthesis of acetyl salicylic acid using a solid acid catalyst.

2. Experimental

2.1. Materials

Salicylic acid and acetic anhydride were supplied by M/S Loba Chemie, India and S.D. Fine Chem. Ltd., India, respectively. Na-forms of zeolites were procured from Zeocat, Switzerland and acid treated K-10 clay was from Sigma–Aldrich, USA.

2.2. Catalyst synthesis

Nano-crystalline sulfated zirconia has been prepared by one step sol–gel technique [12]. A typical synthesis involves the addition of concentrated sulfuric acid (1.02 ml) to zirconium n-propoxide precursor (30 wt%) followed by the hydrolysis with water (water:Zr-P molar ratio 4:1). After 3 h aging at room temperature, the resulting gel was dried at 110 °C for 12 h followed by calcination at 600 °C for 2 h. Sulfated titania was also prepared using the similar methodology. Zeolite H-beta, H-Y, H-ZSM-5 have been prepared by ammonium cation exchanged of the respective Na-forms followed by thermal decomposition [17].

2.3. Catalyst characterization

The crystallinity of all the catalysts and the crystalline phases of calcined sulfated zirconia and titania was determined by X-ray powder diffractometer (Philips X'pert) using CuK_α radiation ($\lambda = 1.54056$ Å). The sample was scanned in 2θ range of 10–80° at a scanning rate of $0.04°\,s^{-1}$. Crystallite size of tetragonal phase of zirconia and anatase phase of titania was determined from their characteristic peak, i.e., at $2\theta = 30.18$ (1 1 1) and 25.30 (1 0 1) for zirconia and titania, respectively by using Scherrer formula [31] as below:

$$\text{Crystallite size} = \frac{K\lambda}{W\cos\theta}$$

where, K, shape factor = 0.9, $W = W_b - W_s$; W_b is the broadened profile width of experimental sample and W_s is the standard profile width of reference silicon sample.

FT-IR spectra of the catalysts were recorded by FT-IR spectrophotometer (PerkinElmer, GX, USA) in the range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1} as KBr pellets.

Specific surface area, pore volume and pore size distribution of all the catalysts were determined from N_2 adsorption-desorption isotherms at −196 °C (ASAP 2010, Micromeritics, USA). Surface area and pore size were calculated by using BET equation and BJH method, respectively [32]. The samples were degassed under vacuum (1×10^{-3} mmHg) at 120 °C for 4 h, prior to adsorption measurement to evacuate the physisorbed moisture.

The bulk sulfur (wt%) retained in sulfated zirconia and titania samples after calcination at 600 °C was analyzed by elemental analyzer (PerkinElmer 2400, Sr II, USA).

2.4. Synthesis of acetyl salicylic acid

O-acetylation of salicylic acid with acetic anhydride was conducted in a batch reactor (20 ml) in presence of solid acid catalyst. Salicylic acid (1 g) and acetic anhydride (3 g) and catalyst (0.1 g, pre-activated at 450 °C for 2 h except K-10, which was pre-activated at 120 °C for 2 h) were taken in a 20 ml reaction tube of reaction station (Radleys Discovery Technologies, UK) equipped with a magnetic stirrer. The mixture was heated at different temperatures in the range of 90–120 °C for reaction times ranging from 30 to 240 min. The reaction mixture was cooled and filtered to separate the catalyst. Unreacted acetic anhydride was hydrolyzed to acetic acid by adding water (10 ml) and the product acetyl salicylic acid was obtained from this solution by the slow evaporation of water at room temperature. The fast recovery of the product was also obtained by adding dichloromethane to the solution, which was separated from the aqueous layer and acetyl salicylic acid was obtained by evaporating the dichloromethane. However, from green synthesis view, we have used the first method without adding dichloromethane throughout this studies. The yield of acetyl salicylic acid was calculated as below:

$$\text{Yield (wt\%)} = \frac{\text{obtained wt. of product}}{\text{theoretical wt. of product}} \times 100$$

The crude yield of acetyl salicylic acid obtained was 92–95%. The crude crystals of acetyl salicylic acid were re-crystallized with ethanol–water mixture and characterized by melting point, DSC and TG-DTA (Mettler Toledo Star^e SW 7.01), FT-IR (PerkinElmer GX, USA), and ^{1}H NMR-spectroscopy (Bruker Avance-II 500).

Table 1
Characterization of various solid acid catalysts used for the synthesis of acetyl salicylic acid.

Catalyst	Method of preparation	Crystalline phase	Crystallite size (nm)	Sulfur (wt%)	Pore diameter (Å)	Surface area (m²/g)
SZ	Sol–gel	Tetragonal	11	1.9	40	97
ST	Sol–gel	Anatase	33	1.3	72	89
H-beta	Cation exchange	–	–	–	7.6 × 6.4	523
H-Y	Cation exchange	–	–	–	7.4 × 7.4	700
H-ZSM-5	Cation exchange	–	–	–	5.1 × 5.5	380
K-10	Commercial	–	–	–	20	270

2.5. Catalyst regeneration

To study the regeneration and re-use of the catalyst, catalyst was recovered from the reaction mixture by filtration and washed with acetone followed by drying at 110 °C for 2 h and thermal activation at 450 °C for 2 h. Thus regenerated catalyst was studied for the synthesis of acetyl salicylic acid under the similar reaction conditions. After every reaction cycle the catalyst was recovered, washed and activated as above.

3. Results and discussion

Table 1 shows the characterization of studied solid acid catalysts. Table 2 shows the yield of acetyl salicylic acid by the O-acetylation of salicylic acid with acetic anhydride using nano-crystallite sulfated zirconia, sulfated titania, zeolite H-beta, H-Y, H-ZSM-5 and acid treated K-10 clay. All catalysts showed yield of acetyl salicylic acid in the range of 65–95%. The catalytic activity was observed in the following order: nano-crystallite sulfated zirconia > sulfated titania = zeolite H-beta > H-Y > H-ZSM-5 > K-10 clay. The observed trend could be explained in terms of acidity and textural properties of these solid acid catalysts. For example, sulfated zirconia and titania are solid acids having the Hammett acidity function $H_0 < -16$ and -14 respectively [9]. Zeolites are known to have the surface acidity $\leq H_2SO_4$ [33] and montmorillonite clays have less surface acidity of $H_0 \sim -5.6$ [34]. Besides the acidity, the larger pore dimensions of the catalyst also contribute in making the reaction more feasible due to easy diffusion of reactants and product molecules. Sulfated zirconia and titania used in the present study are found to have larger pore size (40–70 Å) as compared to the channel dimensions of zeolites (Table 1). However, the correlation between pore diameters of the studied catalysts with the yields of acetyl salicylic acid was not observed. For example, sulfated zirconia and titania having large mesopores (40–70 Å) showed acetyl salicylic acid yields in the range of 80–95 wt%. Zeolites with smaller pore dimension of 5.1–7.6 Å showed acetyl salicyclic acid yields in the range of 70–85 wt%. K-10 clay having mesopores with around 20 Å average diameter showed product yield between 65 and 69 wt%. This showed that pore size alone does not play role in determining the product yield. Pore diameter and surface acidity in terms of number of acid sites and strength jointly determine the catalyst activity. The highest catalytic activity for sulfated zir-

conia could be attributed to its stronger surface acidity and larger pores compared to other studied catalysts. Sulfated zirconia possesses stronger surface acidity due to the presence of sulfate group binding with zirconia surface in an inorganic chelating bidentate fashion (structure A), which showed the characteristic asymmetric and symmetric stretching frequencies of partially ionized S=O double bonds and S–O bonds in the region of 1200–900 cm⁻¹ [35] as shown in FT-IR spectra (Fig. 1). This ionic structure of sulfate group in presence of adsorbed water molecules is responsible for the Brönsted acidity [36] in sulfated zirconia catalysts. The N_2 adsorption–desorption isotherm of sulfated zirconia (Fig. 2) showed type IV isotherm having H2 hysteresis, which is the characteristic of mesoporous materials [32]. The increase in adsorption at higher relative pressure (p/po) showed the presence of larger size mesopores in the sample. Larger pores make accessibility of small reactant molecules (5–7 Å) to the acid sites faster as well as diffusion of the acetyl salicylic acid product (7.7 Å) molecules from the catalyst pores facile and thereby resulting into higher yield of the product. Nano-crystalline sulfated zirconia catalyst has been observed to produce the highest yield of acetyl salicylic acid (92–95 wt%) among all the various catalysts studied. Therefore, a systematic detailed study to optimize the various synthetic parameters for obtaining highest yield of acetyl salicylic acid and the regeneration of the catalyst has been performed over this catalyst.

The kinetic study, to optimize the reaction temperature and time for obtaining the maximum yield of acetyl salicylic acid, was carried out with sulfated zirconia catalyst in the temperature range of 90–120 °C for time ranging from 30 to 240 min. Fig. 3 shows that increase in the temperature from 90 to 120 °C resulted into the increase in the yield of acetyl salicylic acid from 72 to 95 wt%, however, yield was not affected by increasing the time from 30 to 240 min at a particular temperature. The maximum yield (95 wt%) was obtained at 120 °C after 30 min, which did not increase further by increasing the reaction time. At 120 °C, yield was also checked

Table 2
Yield (wt%) of acetyl salicylic acid (ASA) over various solid acid catalysts[a].

Catalyst	ASA (wt%)
SZ	92–95
ST	80–85
H-beta	83–85
H-Y	78–79
H-ZSM-5	70–75
K-10	65–69

[a] Reaction conditions: salicylic acid = 1 g, acetic anhydride = 3 g, catalyst = 0.1 g, reaction temp: 120 °C, and time: 30 min.
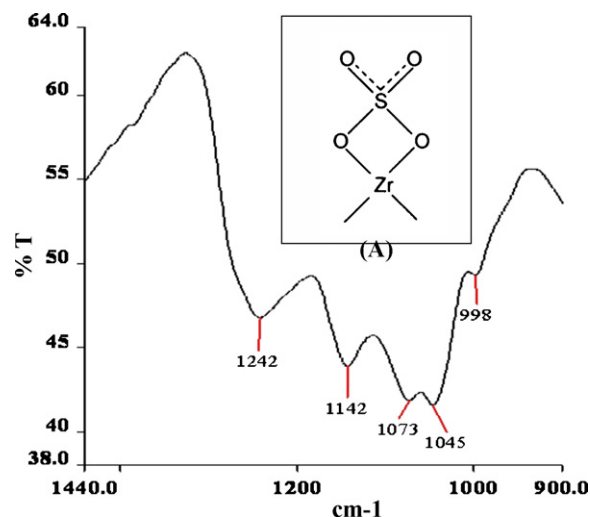

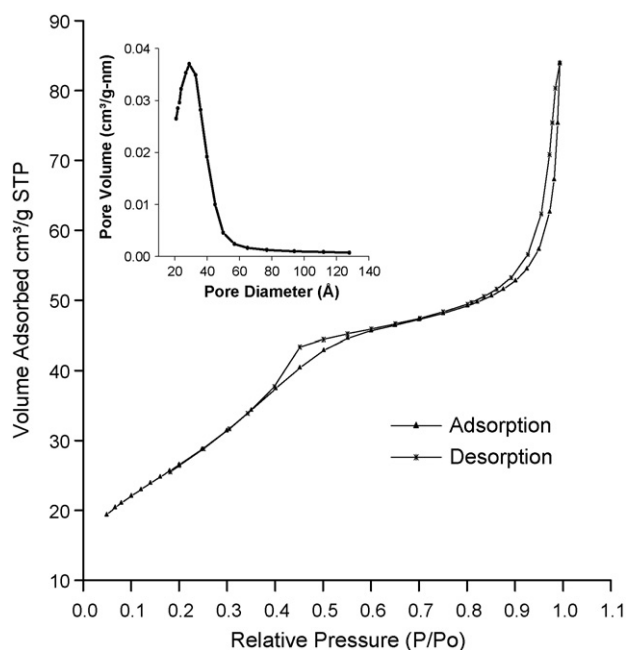**Fig. 1.** FT-IR spectra of nano-crystalline sulfated zirconia.

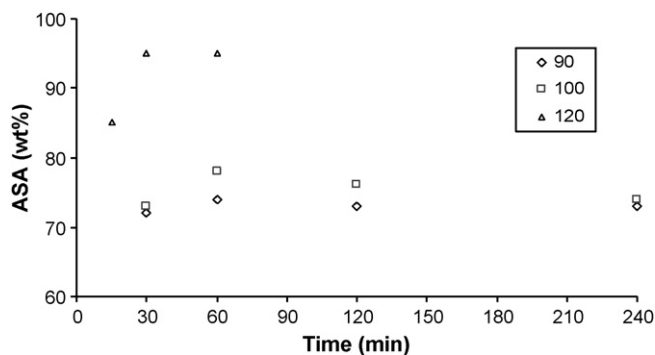**Fig. 2.** N$_2$ adsorption–desorption isotherm and pore size distribution of nano-crystalline sulfated zirconia.

Fig. 3. Effect of reaction temperature (°C) and time (min) on the yield of acetyl salicylic acid over sulfated zirconia catalyst. Reaction conditions: salicylic acid: 1 g, acetic anhydride: 3 g, and catalyst: 0.1 g.

after 15 min and was found to be lower (85 wt%). Therefore, 120 °C and 30 min were chosen as optimized temperature and time for further study. To confirm the yield further, the reaction mixture has been examined after 30 min by HPLC (Shimadzu LC 6AD having CPS Hypersil column), which showed 99.6% conversion of salicylic acid into acetyl salicylic acid.

To study the effect of the molar ratio of salicylic acid to acetic anhydride, the reaction was done at varied molar ratio ranging from 1:2 to 1:5 at optimized temperature, i.e., 120 °C and 30 min with sulfated zirconia catalyst. Table 3 clearly shows the signifi-

Table 3
Yield (wt%) of acetyl salicylic acid (ASA) with varied molar ratio of salicylic acid (SA) to acetic anhydride (AA) over sulfated zirconia catalyst[a].

SA:AA molar ratio	ASA (wt%)
1:2	66–68
1:3	74–75
1:4	92–95
1:5	86–88

[a] Reaction temp: 120 °C, time: 30 min, and SA:SZ wt. ratio = 10:1.

Table 4
Yield (wt%) of acetyl salicylic acid (ASA) with varied salicylic acid (SA) to sulfated zirconia (SZ) catalyst weight ratio[a].

SA:SZ weight ratio	ASA (wt%)
10	95
20	92
30	92
40	90
60	91
80	92
120	90
180	90
250	92

[a] Reaction temp: 120 °C, time: 30 min, catalyst: 0.025–0.1 g, and SA:AA molar ratio = 1:4.

cant effect of the molar ratio on the yield of acetyl salicylic acid. It gradually increased from 68 to 95 wt% with increasing the molar ratio of salicylic acid to acetic anhydride from 1:2 to 1:4. However, further increase in molar ratio to 1:5 resulted into the decrease in the yield (88 wt%). As acetic anhydride acts both as reactant and solvent, it plays a positive role as a solvent till the molar ratio of salicylic acid to acetic anhydride 1:4, wherein, salicylic acid and catalyst were well dispersed in acetic anhydride making the acidic sites accessible to reactant molecule. However, further increase in the concentration of acetic anhydride (molar ratio 1:5) might have dilution effect, thereby decreasing the yield. Therefore, 1:4 molar ratio of salicylic acid to acetic anhydride has been optimized for further studies.

All the above stated reactions for the synthesis of acetyl salicylic acid were performed using 1 g salicylic acid yielding ∼1.23 g acetyl salicylic acid with salicylic acid to catalyst weight ratio of 10:1. To study the effect of substrate to catalyst weight ratio, the reaction was carried out with a wide range of salicylic acid to catalyst weight ratio, i.e., 10:1 to 250:1, wherein the catalyst amount was taken within the range of 0.025–0.1 g and reactants amount was varied accordingly. It is note worthy that with increasing the salicylic acid to catalyst weight ratio from 10:1 to 250:1, the yield of acetyl salicylic acid was not significantly affected (Table 4). Few reactions were also performed to synthesize acetyl salicylic acid in large scale using 10 g of salicylic acid under the similar reaction conditions of molar ratio (1:4), temperature (120 °C) and time (30 min), however, with higher substrate to catalyst weight ratio (100:1 instead of 10:1). The yield of acetyl salicylic acid was found to be in the similar range (95%, 12.4 g). It clearly showed the excellent catalytic activity of sulfated zirconia catalyst towards the synthesis of acetyl salicylic acid by the O-acetylation of salicylic acid with acetic anhydride under the experimental conditions studied.

To study the catalyst life, spent sulfated zirconia catalyst was recovered from the reaction mixture and re-used for the reaction under the similar reaction conditions after washing with acetone followed by drying at 110 °C for 2 h and activation at 450 °C for 2 h. Thus thermally regenerated catalyst was observed to give similar yield of acetyl salicylic acid as the fresh catalyst till 5th reaction cycle (Table 5).

3.1. Characterization of acetyl salicylic acid

The crude crystals of acetyl salicylic acid were re-crystallized with ethanol:water mixture and characterized by melting point, DSC and TG-DTA, FT-IR, and ^{1}H NMR-spectrophotometer as below:

Melting point: 135 °C (from EtOH); DSC: 137.32 °C; TG-DTA: 100 wt% loss in two steps between 140 and 370 °C, first exothermic peak at 150 °C (38 wt% loss) followed by second peak at 350 °C (62 wt% loss).

Table 5
Yield (wt%) of acetyl salicylic acid (ASA) over thermally regenerated sulfated zirconia catalyst[a].

Reaction cycle	ASA (wt%)
1	95
2	93
3	94
4	93
5	95

[a] SA:AA molar ratio 1:4, SA:SZ wt. ratio 10:1, reaction temp: 120 °C, and time: 30 min.

FT-IR (KBr): 3491 cm^{-1} ν_{OH} (–COOH), 1755 cm^{-1} $\nu_{C=O}$ (–COOCH$_3$), 1690 cm^{-1} $\nu_{C=O}$(–COOH).

^{1}H NMR (200 MHz: DMSO: Me$_4$Si): δ 7.9 (d, 1H, ArH), 7.7 (t, 1H, ArH), 7.4 (t, 1H, ArH), 7.2 (d, 1H, ArH), 2.3 (s, 3H, CH$_3$), ~13 (w and br, 1H, –COOH); 2.5 (solvent) and 3.3 (–OH, solvent). The characterization of acetyl salicylic acid was found similar as reported in the literature.

4. Conclusions

Solid acid catalysts such as sulfated metal oxides; zeolites and K-10 clay were found to be green and environmentally benign alternatives to the conventional H$_2$SO$_4$ and H$_3$PO$_4$ for the solvent free synthesis of acetyl salicylic acid by the O-acetylation of salicylic acid with acetic anhydride. Among all the solid acids studied for present synthesis, nano-crystalline sulfated zirconia was found to be a potential catalyst to synthesize high purity crystals of acetyl salicylic acid in excellent yield using minimal amount of catalyst, which can be easily re-used after thermal regeneration without effecting its catalytic activity. Exceptional catalytic activity of sulfated zirconia solid acid catalyst for the synthesis of acetyl salicylic acid shows a good scope to explore its commercial applications and also offers potential to develop a continuous process replacing the batch process.

Acknowledgements

References

[1] J.H. Clark, Acc. Chem. Res. 35 (2002) 791.
[2] A. Corma, Chem. Rev. 95 (1995) 559.
[3] M. Hino, S. Kobayashi, K. Arata, J. Am. Chem. Soc. 101 (1979) 6439.
[4] X. Li, K. Nagaoka, R. Olindo, J.A. Lercher, J. Catal. 238 (2006) 39.
[5] J.M. Grau, J.M. Parera, Appl. Catal. A: Gen. 162 (1997) 17.
[6] D. Farcasiu, J.Q. Li, S. Cameron, Appl. Catal. A: Gen. 154 (1997) 173.
[7] Y.-W. Suh, J.-W. Lee, H.-K. Rhee, Appl. Catal. A: Gen. 274 (2004) 159.
[8] X. Song, A. Sayari, Catal. Rev. Sci. Eng. 38 (1996) 329.
[9] G.D. Yadav, J.J. Nair, Micropor. Mesopor. Mater. 33 (1999) 1.
[10] R.V. Jasra, B. Tyagi, M.K. Mishra, US patent 7,132,582 B2, 2006; Korean patent 0674626, 2007; Indian patent 195683, 2006.
[11] R.V. Jasra, B. Tyagi, M.K. Mishra, Indian patent 1530/DEL/2003, published 28th July, 2006.
[12] B. Tyagi, M.K. Mishra, R.V. Jasra, Catal. Commun. 7 (2006) 52.
[13] B. Tyagi, M.K. Mishra, R.V. Jasra, J. Mol. Catal. A: Chem. 301 (2009) 67.
[14] B. Tyagi, M.K. Mishra, R.V. Jasra, J. Mol. Catal. A: Chem. 276 (2007) 47.
[15] B. Tyagi, M.K. Mishra, R.V. Jasra, J. Mol. Catal. A: Chem. 286 (2008) 41.
[16] V.N. Sheemol, B. Tyagi, R.V. Jasra, J. Mol. Catal. A: Chem. 252 (2006) 194.
[17] V.N. Sheemol, B. Tyagi, R.V. Jasra, J. Mol. Catal. A: Chem. 215 (2004) 201.
[18] M.K. Yadav, C.D. Chudasama, R.V. Jasra, J. Mol. Catal. A: Chem. 216 (2004) 51.
[19] http://en.wikipedia.org/wiki/Aspirin.
[20] D.B. Brown, L.B. Friedman, J. Chem. Educ. 50 (1973) 214.
[21] D.L. Pavia, G.M. Lampman, G.S. Kriz, Introduction to Organic Laboratory Techniques: A Contemporary Approach, Saunders, Philadelphia, 1976, pp. 27–30.
[22] (a) J.A. Miller, E.F. Neuzil, Modern Experimental Organic Chemistry, Heath, Lexington, MA, 1982, pp. 192–197;
(b) K.L. Williamson, Macroscale and Microscale Organic Experiments, 2nd ed., Houghton Mifflin, Boston, 1994, pp. 379;
(c) J. Olmsted III, J. Chem. Educ. 75 (1998) 1261.
[23] D.Y. Hung, G.D. Mellick, R.J. Prankerd, M.S. Roberts, Int. J. Pharma. 153 (1997) 25.
[24] S. Pandita, S. Goyal, J. Chem. Educ. 75 (1998) 770.
[25] Y. Peng, G. Song, Chem. Educ. 5 (144) (2000).
[26] G.A. Mirafzal, J.M. Summer, J. Chem. Educ. 77 (2000) 356.
[27] A.K. Bose, B.K. Banik, N. Lavlinskaia, M. Jayaraman, M.S. Manhas, Chemtech (1997) 18.
[28] A.K. Bose, M.S. Manhas, S.N. Ganguly, A. Sharma, M. Huarotte, S. Rumthao, M. Jayaraman, B.K. Banik, Fifth International Electronic conference on Synthetic Organic Chemistry (ECSOC-5), 2001, http://www.mdpi.org/ecsoc-5.htm.
[29] I. Montes, D. Sanabria, M. Garcia, J. Castro, J. Fajardo, J. Chem. Educ. 83 (2006) 628.
[30] R.V. Jasra, B. Tyagi, M.K. Mishra, US patent 7,544,831 B2, 2009.
[31] B.D. Cullity, S.R. Stock, Elements of X-ray Diffraction, 3rd ed., Prentice Hall, Upper Saddle River, NJ, 2001, pp. 388.
[32] S.J. Gregg, K.S.W. Sing, Adsorption, Surface Area and Porosity, 2nd ed., Academic Press, New York, 1982.
[33] A. Corma, Curr. Opin. Solid State Mater. Sci. 2 (1997) 63.
[34] M. Frenkel, Clays Clay Miner. 22 (1974) 435.
[35] T. Yamaguchi, T. Jin, K. Tanabe, J. Phys. Chem. 90 (1986) 3148.
[36] M.K. Mishra, B. Tyagi, R.V. Jasra, Ind. Eng. Chem. Res. 42 (2003) 5727.