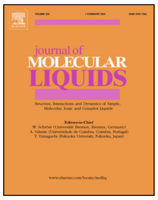
Journal of Molecular Liquids 334 (2021) 116523

Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq



Effect of molecular structure of cation and anions of ionic liquids and co-solvents on selectivity of 5-hydroxymethylfurfural from sugars, cellulose and real biomass

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ARTICLE INFO

Article history:
Received 4 April 2021
Revised 1 May 2021
Accepted 16 May 2021
Available online 19 May 2021

Keywords:
5-Hydroxymethylfurfural
Platform chemical
Biorefinery
Bronsted Lewis acidic ionic liquid
Organic electrolyte solutions
Co-solvents

ABSTRACT

The concept of biorefinery still requires advancements in process development for energy and materials. Ionic liquids have been successfully used for several biorefinery applications including high yield synthesis of biofuels and value added platform chemicals. Designing suitable ionic liquid that is efficient in terms of cost as well as product selectivity is still highly needed. This study is carried out to check the effect of different anions of Bronsted acidic ionic liquids (BAILs), Bronsted Lewis acidic ionic liquids (BLAILs), Lewis acidic ionic liquids (LAILs) as well as organic electrolyte solutions (OES) for 5-HMF selectivities from monosaccharides, polysaccharides as well as lignocellulosic composite. Different variables and parameters such as Lewis acidity of anions, alkyl side chain of ionic liquid, metal chloride type and loading, time, temperature, substrate loading, polar protic and aprotic solvents are thoroughly studied for process optimization. Polar protic solvents added in [$C_1C_4SO_3HPy$] based ionic liquids with CH_3COO^- and Cl^- anions yielded 94 and 80% 5-HMF from fructose and glucose respectively in the presence of $AlCl_3$ as Lewis acid. C_4SO_3H side chain yielding high from fructose and glucose is inefficient for conversion of cellulose and lignocellulose. High product selectivity from these biopolymers is achieved using butyl side chain with 3-methylpyridinium cation and chlorochromate anion.

1. Introduction

Selective conversion of biomass-derived renewable carbon-rich materials into biofuels and sustainable platform chemicals has been an immense techno-economic challenge in view of constantly depleting fossil resources and unceasingly increasing energy demands. According to a report by US Department of Energy and US Department of Agriculture, it is estimated that 1.3 billion tons of dry biomass can be obtained per annum without substantial modifications in food supplies and agricultural practices. If it happens successfully, 20% of the total demanded transportation fuel can be produced by 2030 [1] in biorefineries, but the condition is; a cost-effective, environmentally friendly and feasible bulk production method must have been developed.

From all the current annual production of waste biomass, carbohydrates constitute up to 170×10^9 tons; approximately 75% of the total biomass [2]. Monomeric units of these carbohydrate biopolymers are the precursors of diverse set of platform chemicals such as 5-hydroxymethylfurfural (5-HMF). 5-HMF is one of the top ten value added chemicals as reported by US Department of Energy [3]. It is a key substance for biomass derived carbohydrate chemistry as well as petrochemical based industrial chemistry. It serves as valuable intermediate for biofuels and industrially important platform chemicals due to its multi-functionality as well as high reactivity. Going from waste to end product none of the carbon is lost thus carbon economy is also a promising thing.

Conversion of carbohydrates into 5-HMF requires acidic conditions and water is the only co-product when 100% selectivity is reached. The selectivity is a function of tautomeric distribution of fructose and it is affected with temperature, reaction time and nature of solvent used [4]. From various solvents used so far, near-quantitative yield is obtained only in ionic liquids (ILs) [5] or non-aqueous, polar aprotic solvents such as dimethyl sulfoxide or 2-methyl-2-pyrrolidone [6]. Organic solvents, water-organic mixtures and other systems used so far suffer with various drawbacks like solvents recycling and environmental problems. Thus, ILs with highly green profile are the most recommended for conversion of fructose into 5-HMF. Processing in ILs improved the

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https://doi.org/10.1016/j.molliq.2021.116523

process efficiency and products selectivity by reducing the formation of humins and other side-products. It enhances the rate of reaction even for more complex carbohydrates; glucose, cellobiose, starch and cellulosic polymers.

ILs are actually the molten organic salts with less than 100 °C melting points due to poorly coordinated organic heterocyclic cations (mostly nitrogen or phosphorus as heteroatom) and an inorganic anion. The poor coordination is attributed to the steric hindrance due to large size of cation [7]. These are highly designed solvents as their features and properties can be adjusted by wise selection of cation and anion pair. Cations are responsible for viscosity, melting points and electrochemical stability variations. While anions are accountable for hydrogen bonding and in turn for miscibility with other solvents or water [8].

Conversion efficiencies of ILs as well as product selectivities are also markedly affected by molecular structure of both anion and cations. Mostly, the catalytic activity is dependent on anion type particularly due to the role of hydrogen bonding and acidity in conversion and product selectivities [9]. From previous reports, it can be concluded that ILs with chloride anion possess high dissolution abilities for carbohydrates while switching their anion to tetrafluoroborate or hexafluorophosphate improve their conversion efficiency for furan related compounds [10,11]. Dehydration related mechanism is highly promoted by hydrogen sulfate anion due to its strong acidic character [12]. But this anion is almost ineffective for glucose/cellulose to 5-HMF conversion where additional saccharification and isomerization steps are involved; suggesting that it actually inhibits the glucose–fructose inter-conversion [13]. Adding some Lewis acidic character with chloride anion makes it appropriate for conversion of glucose and cellulose into 5-HMF. Basically the coordination ability of metal center in Lewis acids and their additional halide ligands coordinated with IL chloride anion improves the rate of glucose isomerization [14]. Hence, the careful selection of anion is most important for desired application of IL. Talking about cation, both the cation and alkyl chain is important for conversion process. Wang et al. reported that the product 5-HMF exhibits hydrogen bonding with anion of IL, weak interactions with imidazolium cation via C═O functionality and almost no interaction was detected between 5-HMF and alkyl chain of the cation [15].

Besides inserting Lewis acidic character in IL, 5-HMF selectivities can also be enhanced by formation of organic electrolyte solutions (OES). OES is formed by addition of some polar organic co-solvent in IL to reduce its viscosity and enhance its thermal stability [16]. Addition of polar protic or polar aprotic solvent in IL increases the yield of 5-HMF by suppressing the rate of side reactions and thus increasing the 5-HMF selectivity.

In this study, we used an unsymmetrical 3-methyl pyridinium cation based on its four times less price as compared to the highly investigated imidazolium ILs [17] and its best efficiencies for dissolution and conversion of lignocellulosics [18,19] according to our previous findings. Quaternization is done by butane sulfonic acid and 1-chlorobutane based on the best dissolution and conversion efficiencies of C_4 side chain [18] and best dehydration efficiencies of SO_3H groups [13]. With these cationic cores, ten different anions are tested for their dehydration, saccharification and isomerization power with/without metal chloride and co-solvents.

2. Materials and methods

3-Methylpyridine (Sigma Aldrich), 1,4-butanesultone (Sigma Aldrich), 1-chlorobutane (Fischer Scientific), sulfuric acid (Acros), hydrochloric acid (Sigma), acetic acid (Sigma), trichloroacetic acid (Aldrich), trifluoroacetic acid (Merck), benzene sulfonic acid (Sigma Aldrich), *para*-toluene sulfonic acid (Sigma Aldrich), 70% aq. solution of methanesulfonic acid (Alfa Aesar), taurine (Sigma Aldrich) and metal chlorides were of analytical grade and used without any further purification. All the solvents such as *n*-hexane, ethyl acetate and HPLC grade acetonitrile were purchased and distilled before use. (D)(−)-Fructose (Daejung), *D*-galaxose and microcrystalline cellulose were purchased and used as such. Wheat husk as lignocellulosic feedstock was harvested from a local farm in Punjab, Pakistan. It was ground and meshed to collect particle sizes of 100, 250 and 500 μm for investigation. The samples were dried at 70 °C for 48 h to remove moisture before processing in ILs. Standard of 5-hydroxymethylfurfural was purchased from Sigma Aldrich and used as received.

2.1. Synthesis of ILs

2.1.1. Synthesis of 1-butylsulfonic-3-methylpyridinium based ILs (IL 1–10)

Equimolar 3-methylpyridine and 1,4-butanesultone were taken in a 100 mL round bottom flask and heated at 50–60 °C with continuous stirring for one hour to form Zwitterionic white solid (C_1-$C_4SO_3^-Py^+$). This white solid was washed with distilled ethyl acetate to remove any unreacted 3-methylpyridine present in it and then analyzed by ^1H NMR (See SI).

White solid, Yield (>95%), ^1H NMR (400 MHz, D_2O) δ (ppm): 1.621–1.723 (2H, m, CH_2), 1.994–2.095 (2H, m, CH_2), 2.425 (3H, s, CH_3), 2.84 (2H, t, J = 10 Hz, CH_2), 4.49 (2H, t, J = 10 Hz, CH_2), 7.798 (1H, t, J = 8.4 Hz, Ar-H), 8.236 (1H, d, J = 10.4 Hz, Ar-H), 8.536 (1H, d, J = 8.4, Ar-H), 8.595 (1H, s, Ar-H).

The vacuum-dried white solid was then refluxed at 80 °C with 1 eq. of different HXs (where X = HSO_4^-, Cl^-, CH_3COO^-, CF_3COO^-, CCl_3COO^-, $PhSO_3^-$, $CH_3PhSO_3^-$, $NH_2SO_3^-$, $CH_3SO_3^-$) to produce completely viscous ILs.

2.1.2. Synthesis of 1-butyl-3-methylpyridinium chloride $[C_4C_1Py]Cl$

In a 100 mL round bottom flask, 1 eq. of 3-methylpyridine and 1.1 eq. of 1-chlorobutane were added and refluxed at 110 °C with continuous stirring at 120 rpm. Progress of reaction was monitored via TLC using 50% ethyl acetate: *n*-hexane solvent system. Reaction was continued for 35–40 h until the formation of considerable amount of product. After that, the product was washed several times with ethyl acetate to ensure the complete removal of unreacted 3-methylpyridine. The final single spotted pure IL was stored in an oven dried vial and sealed to prevent the moisture.

White solid, Yield (85%), ^1H NMR (400 MHz, D_2O) δ (ppm): 0.85 (3H, t, J = 7.6 Hz, CH_3), 1.24–1.29 (2H, m, CH_2), 1.88–1.93 (2H, m, CH_2), 2.46 (3H, s, CH_3), 4.83 (2H, t, J = 7.2 Hz, CH_2), 7.85 (1H, t, J = 6.8 Hz, Ar-H), 8.27 (1H, d, J = 8 Hz, Ar-H), 8.56 (1H, d, J = 5.6, Ar-H), 8.62 (1H, s, Ar-H).

2.2. Synthesis of 5-hydroxymethylfurfural (5-HMF)

IL (400 mg) was taken in an oven-dried vial followed by the addition of metal salt (10 wt%). It was heated at 80–100 °C with continuous stirring at 100 rpm until the formation of IL–MCl complex. After that, 10 wt% fructose, glucose, cellulose or wheat husk was added into it and stirred at specified temperature (80–130 °C) for specific time (1–7 h). After completion of reaction, the reaction mixture was cooled and subjected to qualitative and quantitative analyses.

2.3. Analysis of products

2.3.1. HPLC analysis

Quantification of produced 5-HMF was performed using D-Star HPLC instrument with UV–Vis detector equipped with Discovery, HS C18 column; 5 μm particle size (25 cm × 4.6 mm) using acetonitrile as mobile phase at room temperature and flow rate of 1.0 mL/min.

After the completion of reaction, 5 mg crude reaction mixture was withdrawn and diluted with HPLC grade acetonitrile. Solution was mixed well, centrifuged, syringe filtered and then 20 μL of it was injected to HPLC for analysis at 282 nm. Yield was calculated according to the following formulas [20];

$$M_{HMF}(mg) = C_{HMF}\left(\frac{mg}{mL}\right) \times DF \times \frac{M_o}{M_1}$$

$$HMF\ \ Yield\ (\%) = \frac{\text{5HMF produced}\ \left(\frac{\text{mg}}{\text{mL}}\right)}{\text{intial fructose (mg)}} \times 100\%$$

where M_{HMF} (mg) is the amount of 5-HMF produced, C_{HMF} (mg/mL) is the concentration of 5-HMF as obtained from standard 5-HMF calibration curve, DF (mL) is the dilution factor, M_o and M_1 (mg) are the respective masses of total reaction mixture and sample withdrawn for HPLC analysis.

2.3.2. ^{1}H NMR analysis

Proton NMR of 5-HMF was recorded in $CDCl_3$ at 600 MHz, Bruker's Avance Neo Technology. For analysis, 5-HMF was extracted by distilled ethyl acetate and subjected to column chromatography using silica as adsorbent to remove any possible IL present in it. Ethyl acetate was evaporated using rotary evaporator to afford pure 5-HMF.

2.3.3. GC–MS analysis

GC–MS spectrum of ethyl acetate soluble product was recorded using GC TRACE-1300 and MS-ISQ with auto sampler AI-1310 (Thermo Scientific), column type TR-35 (30 m × 0.25 mm, 25 μm) using Helium (99.99%) as carrier gas.

2.3.4. Analysis of unreacted sugars

Unreacted fructose and glucose present in reaction mixture was quantified via DNS assay. 20 mg of crude sample was withdrawn from reaction mixture and diluted 150 times with DI water. Dinitrosalicylic acid solution (1 mL) was added into it and resultant solution was boiled well for 15 min and analyzed by UV–spectrophotometer (UVD-3500, Labomed, Inc. USA) at 540 nm [21]. Concentration of unreacted sugars was determined from glucose calibration curve while the percentage was calculated by this equation [22]:

$$Y_{TRS} = \frac{C_{TRS} \times M_2 \times 150}{M_b \times 1.11 \times \frac{M_2}{M_o}} \times 100\%$$

Y_{TRS} is the percentage of sugars left unreacted, C_{TRS} (mg/mL) is the concentration of reducing sugars obtained from standard calibration curve for glucose, 150 is in multiples of diluted sample, M_o and M_2 (mg) are the respective masses of total reaction mixture and sample withdrawn for sugars analysis, M_b (mg) is the total mass of sugars precursor added to the reaction and 1.11 is the ratio of molecular weight of sugar $C_6H_{12}O_6$ to that of cellulosic content $C_6H_{10}O_5$ of biomass.

2.4. Regeneration and recycling of ILs

After products extraction, residual IL phase was subjected to heat to remove any possible ethyl acetate in it. Percentage recovery of regenerated IL was calculated relative to the initial amount of IL used in the reaction.

$$Recovered\ \ IL(\%) = \frac{\text{weight of dried recovered IL}}{\text{weight of iniatially used IL for reaction}} \times 100$$

This recovered catalytic system was then recycled in the next runs by adding fresh sugars under the same reaction conditions and the recyclability of system was noted.

2.5. Design of experiments (DOE)

All the experiments were performed in triplicates and the effect of all independent variables (anion of BAIL, MCl loading, reaction time, temperature, substrate loading and co-solvent addition) on the response (5-HMF, percentage conversion and product selectivities) was analyzed. All the yields reported in this study are the average values of triplicate experiments.

3. Results and discussion

3.1. Characterization of 5-HMF

Confirmation of 5-HMF was done via UV, HPLC, ^{1}H NMR and GC–MS analyses. 5-HMF was extracted by distilled ethyl acetate as yellow oily liquid exhibiting λ_{max} of 280 nm in UV–Vis spectrophotometer (Fig. 1). HPLC analysis was carried out at the same wavelength using acetonitrile as eluent with flow rate of 1.0 mL/min. Peak of standard 5-HMF as well as synthesized product was observed at 2.7 min (Fig. 2). Proton NMR analysis in $CDCl_3$ (Fig. 3) confirmed the 5-HMF as sole product of reaction. Singlet for aldehyde peak was observed at 9.46 ppm, doublets of furan ring protons appeared at 7.1 and 6.4 ppm with coupling constants of 3.6 and 3.0 respectively. Two protons of alcoholic –—CH_2O appeared as singlet at 4.61 ppm. Peak at 126 *m*/*z* with 100% intensity in GC–MS (Fig. 4) also confirmed the 5-HMF. Other peaks in GC–MS are as follow; M.S. *m*/*z* (% of max intensity): 53.11 (10), 69.06 (24), 79.04 (12), 97.00 (80), 125.97 (100), 127.11 (08).

3.2. Factors affecting the synthesis of 5-HMF; process optimization using monosaccharides

3.2.1. Effect of anions

Ionic liquids are highly designed solvents that can be tuned according to the desired process by sensible selection of cation and anion pair to modify their vast adjustable striking features like thermal stability, electrochemical properties, vapor pressure and others [23]. Biomass dissolution, saccharification, deconstruction as well as conversion efficiencies of ILs are also varied by changing their cations, anions as well as alkyl side chains. In our previous studies, we approved the high dissolution and conversion efficiencies of pyridinium cation of ILs [19,24,25] and butane side chain [18,19]. So, in this study, we fixed the unsymmetrical pyridinium

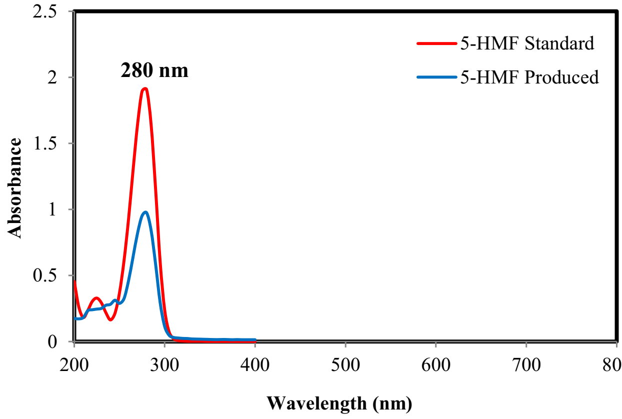

Fig. 1. UV analysis of 5-HMF.

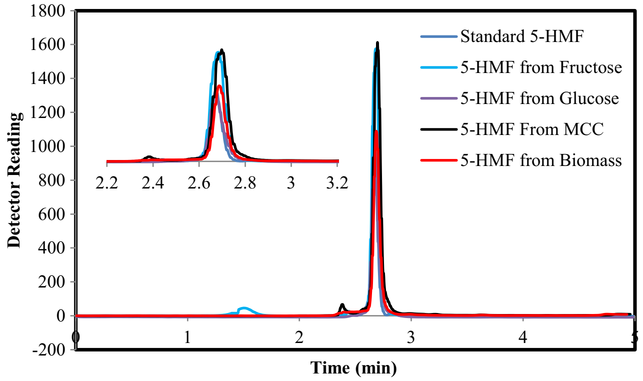

Fig. 2. HPLC chromatograms of standard and synthesized 5-HMF.

cation with butylsulfonic side chain and the effect of ten different anions; hydrogen sulfate, chloride, acetate, trifluoroacetate, trichloroacetate, *para*-toluene sulfonate, benzene sulfonate, amino sulfonate and methane sulfonate is studied for conversion of fructose and glucose into 5-HMF.

At first, Bronsted acidic ILs were heated with 10 wt% keto sugar at 80 °C for one hour. *Para*-toluene sulfonate anion of ionic liquid was observed as most effective for fructose dehydration yielding 75% 5-HMF with 82% selectivity. The conversion ability for other anions was observed as Cl^- > CF_3COO^- > CH_3COO^- > CCl_3COO^- > $CH_3SO_3^-$ > $NH_2SO_3^-$ > $PhSO_3^-$ and HSO_4^- (Table 1). The trend is approximately in agreement with the hydrogen bond acceptor strength of the anions; as anion of IL is responsible for formation of hydrogen bonding with –OH groups of fructose and that of 5-HMF [15] thus increasing the acidic strength. So, stronger hydrogen bond acceptor as anions increases the acidity of IL, promoting its catalytic performance for dehydration. Lower activity of HSO_4^- and clustered $HSO_4^-.H_2SO_4$ anions in ILs 1&2 can be justified by findings of Shi et al. [26] who also reported the low efficiency of HSO_4^- as compared to $CH_3SO_3^-$. Another report by research group of Zeitsch using sulfuric acid as mineral acid catalysis also suggests that sulfonation of furan ring may happen by hydrogen sulfate anions leading to the undesired by-products [27]. Results are also in agreement to the findings of Wang et al. who described the hydrogen bond forming order of different anions as: acetate, propionate > hydrogen sulfate > trifluoroacetate > dicyanamide > nitrate > methane sulfonate > tetrafluoroborate [15].

Conversion of glucose into 5-HMF is comparatively difficult as it requires high activation energy due to additional isomerization step prior to dehydration. So, the main thing in conversion is wise selection of catalyst or some other isomerization accelerating parameter [28]. Initially, we used same BAILs for glucose to 5-HMF conversion. It was observed that IL-3 having chloride anion is more effective for isomerization probably due to small size of anion and high hydrogen bonding ability with –OH groups of glucose. After Cl^-, best anion was $CH_3PhSO_3^-$ present in IL-7 yielding 12% 5-HMF. All other anions were almost inactive for isomerization yielding significantly low yields.

All ILs were then made Bronsted Lewis acidic by heating them with 10 wt% of metal chlorides. Aluminum and chromium chlorides were used for this purpose in view of their better efficiencies

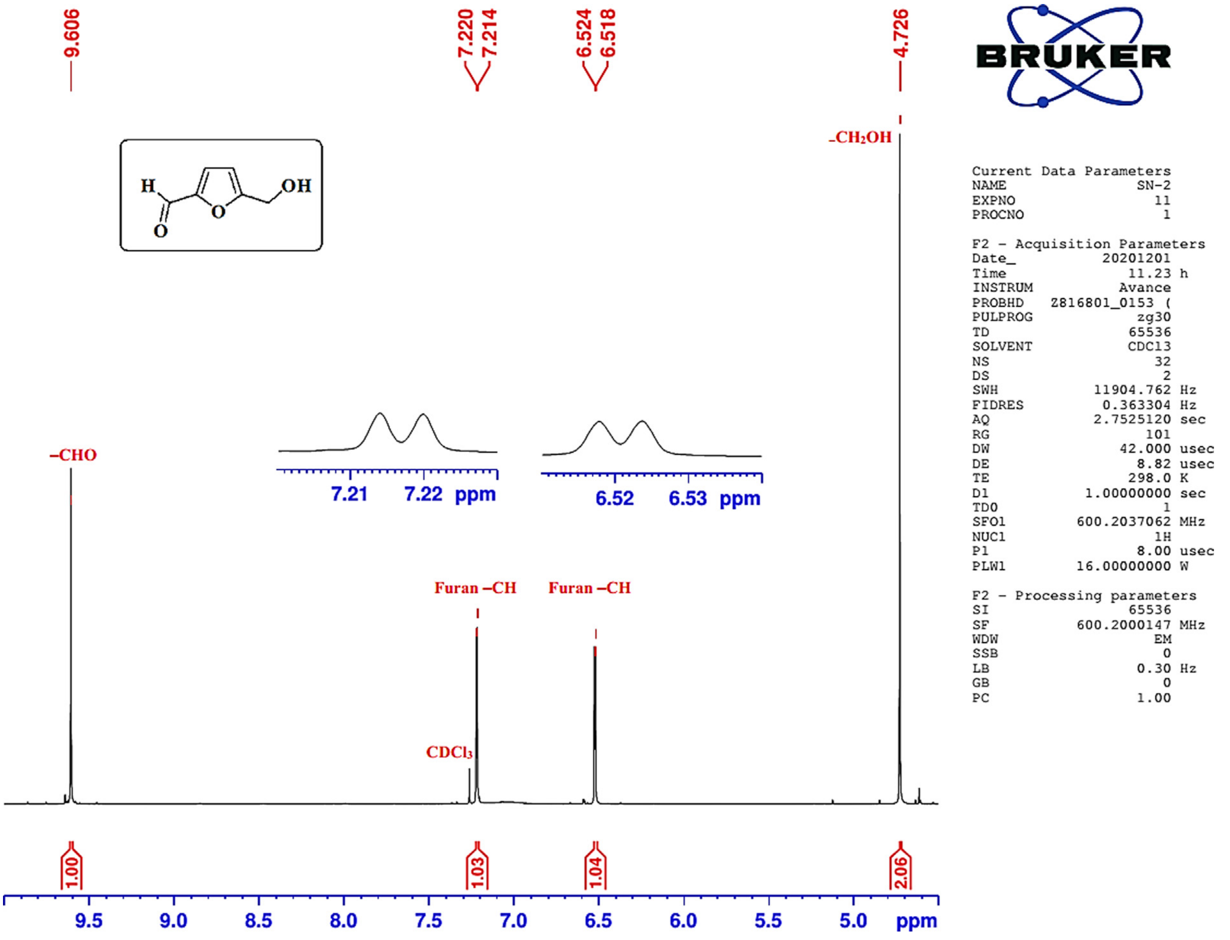

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Fig. 3. ^1H NMR of synthesized 5-HMF.

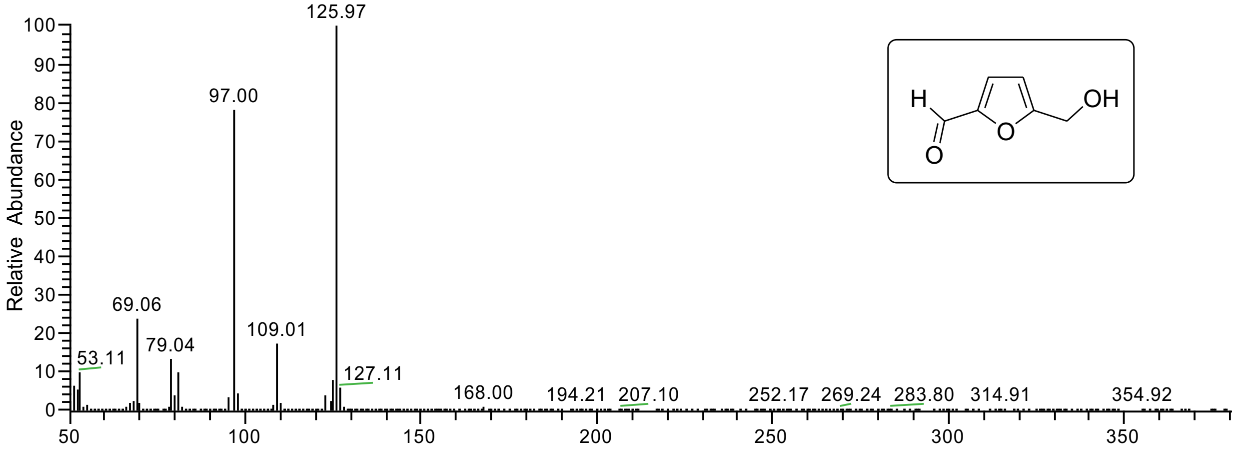

Fig. 4. Mass spectra of gas chromatography–mass analysis of synthesized 5-HMF.

Table 1
Effect of IL anions with [$C_4SO_3HC_1Py$] cation on synthesis of 5-HMF.

Substrate	ILs [$C_4SO_3HC_1Py$][X]Where X =	5-HMF (%)	Unreacted fructose[a] (%)	Percentage conversion[b] (%)	5-HMF selectivity[c] (%)
Fructose	HSO_4^-	0.1	5	95	0.1
	$HSO_4^-.H_2SO_4$	0.1	4	96	0.1
	Cl^-	74	3	97	76
	CH_3COO^-	68	10	90	76
	CF_3COO^-	71	08	92	77
	CCl_3COO^-	65	09	91	71
	$CH_3PhSO_3^-$	75	08	92	82
	$PhSO_3^-$	38	30	70	54
	$NH_2SO_3^-$	56	22	78	72
	$CH_3SO_3^-$	61	14	86	71
Glucose	HSO_4^-	0.01	10	90	0.01
	$HSO_4^-.H_2SO_4$	0.01	10	90	0.01
	Cl^-	20	34	30	30
	CH_3COO^-	0.03	89	11	0.27
	CF_3COO^-	01	79	21	4.76
	CCl_3COO^-	01	75	25	04
	$CH_3PhSO_3^-$	12	66	34	35
	$PhSO_3^-$	0.001	90	10	0.01
	$NH_2SO_3^-$	02	78	22	09
	$CH_3SO_3^-$	10	65	35	29

[a] Unreacted fructose calculated by TRS%.
[b] Conversion (%) = 100 – Unreacted fructose.
[c] 5-HMF Selectivity (%) = (Yield of 5-HMF/Percent Conversion) × 100%.

as reported in literature and also supported by our previous studies [19]. Efficiencies of ILs increased > 20% in terms of yields and selectivities of product due to infused Lewis acidic character. From all produced BLAILs, best dehydration ability is observed for chloroaluminates of [$C_4SO_3HC_1Py$]CH_3COO (IL-4) and [$C_4SO_3HC_1Py$]CF_3COO (IL-5). ILs [$C_4SO_3HC_1Py$][$AlCl_4$] and [$C_4SO_3HC_1Py$][$AlCl_4CCOO$] also played well yielding 73 and 80% respectively. Almost the same trend is observed with chlorochromates but with comparatively lower yields (Table 2). Difference in efficiency of various metals is justified on the basis of their coordination ability; the metals with greater coordination ability decrease the yield [14]. Evidences also suggest the acceleration of some other side reactions due to strong Lewis acids [29].

Talking about glucose, [$C_4SO_3HC_1Py$][$AlCl_4$] showed best isomerization and dehydration efficiencies. The chloroaluminate complex formed between aluminum chloride and IL anion plays a role in proton transfer and facilitates mutarotation of α-anomeric glucose to its β-anomer via hydrogen bonding between the chloride anions and glucose hydroxyl groups. The aldose ring is then opened to its straight chain structure combining with chloroaluminate complex to produce enolate intermediate thus enabling the conversion of aldose sugar into ketose sugar. This keto- sugar is then dehydrated readily yielding 5-HMF [30].

3.2.2. Effect of MX (wt%) loading

Yields of hydrolysis, dehydration and isomerization are also affected by concentration of metal chloride used for imparting Lewis acidity in IL. Amount of metal chloride alters the equilibrium of hydrolysis as well as levels of active species. Strong Lewis character accelerates some other side reactions lowering the yield of targeted products [29].

Effect of aluminum chloride loading on dehydration of fructose was noted with IL-4 and IL-5 as best dehydration efficiency of these two ILs containing acetate and trifluoroacetate anions was noted before. With IL-4, just a little amount of $AlCl_3$ (3 wt%) was effective to yield 95% 5-HMF at 80 °C in only one hour. Up to 10 wt% loading, the yield of 5-HMF is almost constant or a minor decrease is observed. Above 10 wt% addition, a clear decrease in yield is observed. With IL-5, conversion of fructose is increased initially with the loading of $AlCl_3$ up to 10 wt% (87% maximum yield), above which a sharp decrease in yield is observed; 44% 5-HMF is produced with 13 wt% $AlCl_3$. High levels of metal chloride present

Table 2
Effect of metal chlorides to infuse Lewis Acidic character in IL for the synthesis of 5-HMF.

ILs	5-HMF Yield (%)			
	Fructose		Glucose	
	$AlCl_3$	$CrCl_3$	$AlCl_3$	$CrCl_3$
$[C_4SO_3HC_1Py][HSO_4]$ IL-1	22	86	00	00
$[C_4SO_3HC_1Py][HSO_4.H_2SO_4]$ IL-2	02	00	00	00
$[C_4SO_3HC_1Py][Cl]$ IL-3	73	10	25	08
$[C_4SO_3HC_1Py][CH_3COO]$ IL-4	94	81	0.01	05
$[C_4SO_3HC_1Py][CF_3COO]$ IL-5	91	65	10	04
$[C_4SO_3HC_1Py][CCl_3COO]$ IL-6	80	63	13	00
$[C_4SO_3HC_1Py][CH_3PhSO_3]$ IL-7	30	78	12	14
$[C_4SO_3HC_1Py][PhSO_3]$ IL-8	01	01	0.01	00
$[C_4SO_3HC_1Py][NH_2SO_3]$ IL-9	59	48	05	00
$[C_4SO_3HC_1Py][CH_3SO_3]$ IL-10	56	55	13	15

in reaction mixture heighten the rehydration of 5-HMF yielding levulinic acid as by-product. The reason lies in increasing the proton concentration due to the hydrolysis of metal chloride. Additionally, probabilities for formation of other by-products are also enhanced due to the condensation of 5-HMF and other intermediates to polymers promoted by elevated number of protons in reaction media [31].

Impact of $AlCl_3$ loading on glucose conversion is noted with IL-3 having chloride as counter anion. As shown in Fig. 5 the yield of 5-HMF is increased first and then decreased with the addition of $AlCl_3$. A maximum of 25% 5-HMF is obtained with 7 wt% $AlCl_3$. Mixed metal catalysis was also applied to check if glucose conversion rate is increased or not. Considering the 7 wt% as optimum $AlCl_3$ loading for glucose conversion in IL-3; 1:1 ratio of $AlCl_3$ and $CrCl_3$ was added into the IL-3 and yield of 5-HMF was noted to decrease (just 07% yield in 1 and 2 h). Increasing the time of reaction, only 4 and 5% 5-HMF is obtained after 3 and 4 h respectively. Hence, the mixed metal catalysis is totally ineffective for this conversion.

3.2.3. Effect of time

Taking into consideration the best IL anion and Lewis acidic strength caused by $AlCl_3$ loading, batch reactions were performed for conversion of fructose with IL-4 and that of glucose with IL-3 for different time intervals ranging from one to seven hours (Fig. 6). The rate of fructose dehydration was almost constant from one to five hours yielding 70, 70, 72, 72 and 74% 5-HMF. After that, it is decreased to 67 and then 66% at 6 and 7 h respectively. This decrease in 5-HMF yield is justified by production of humins after five hours. Due to the deliberate yield increment from one to five hours, one hour reaction time was considered as optimal and further experimentation was done using the same to save energy and enhancing the process efficiency according to green chemistry protocols.

Similarly for glucose, 5-HMF selectivity was decreased sharply after one hour reaction time; 26% yield is obtained at one hour decreasing to 8% in the second hour and so on. As the reaction continued, color of reaction mixture is intensified evidencing the decomposition of produced 5-HMF. In acidic conditions, decomposition takes place usually by rehydration of 5-HMF to yield levulinic acid and formic acid, by hydrolytic ring-opening of 5-HMF into an aliphatic open-chain intermediate and its subsequent self-polymerization or by cross-polymerization between 5-HMF and unreacted saccharides [32,33]. Chances of rehydration are less in water-free systems like ours. So, the only possibility here is to form insoluble humins and brown soluble polymers via 5-HMF polymerization. These polymerization products can visually be detected as

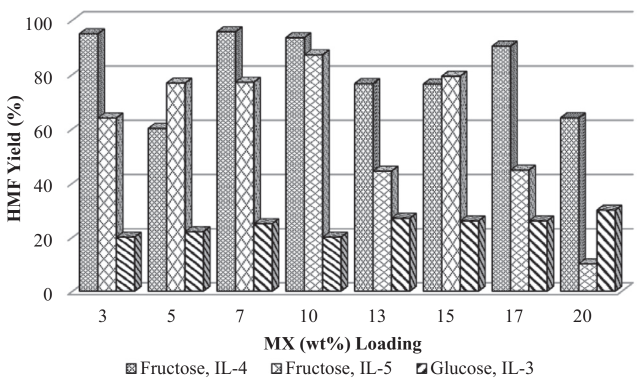

Fig. 5. Effect of wt% loading of $AlCl_3$ in different ILs on percentage yields of 5-HMF.

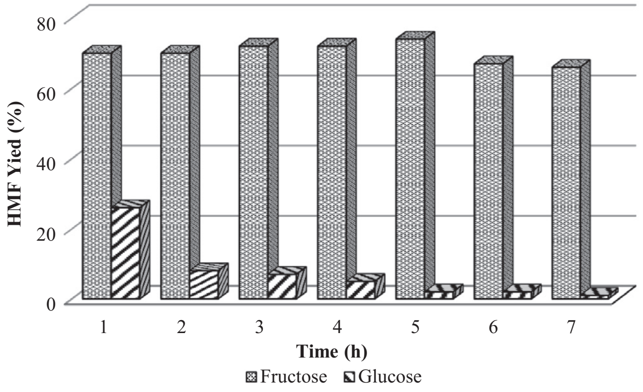

Fig. 6. Effect of time on 5-HMF production.

very fine dark color particles in HPLC samples prepared by adding acetonitrile in IL reaction system.

3.2.4. Effect of temperature

Temperature of reaction is an important parameter for isomerization of aldose sugar, dehydration of ketose sugar as well as for product selectivities. To examine the effect of temperature, conversion of fructose and glucose was performed in batch reactions at 60, 80, 100, 120 and 130 °C. It could be noticed that when the treating temperatures for fructose exceed from 100 °C, a sharp reduction in 5-HMF yield occurs due to inevitable formation of humins and degradation of sugars at higher temperatures. Thus 100 °C can be fixed as the near-limit-value for fructose. Relatively more activation energy is required for conversion of glucose [34]. At 80 °C, only 20% yield is obtained from glucose indicating that low temperature hindered its isomerization to fructose. Also, above 120 °C the conversion rate seems to be kinetically incompatible in terms of 5-HMF selectivities (Fig. 7).

3.2.5. Conversion in organic electrolyte solutions (OES)

Recent studies state that polar organic solvents added in ILs such as dimethyl sulfoxide (DMSO), *N,N*-dimethylacetamide (DMA) and *N,N*-dimethyl-formamide (DMF), tend to improve the selectivities of 5-HMF by suppressing the rate of side reactions. By using these organic solvents as co-solvent with IL, separation of 5-HMF is also done easily by distillation of these low boiling solvents.

Five different co-solvents; deionized water, dimethyl sulfoxide, methanol, ethanol and isopropanol were used with ILs in 1:3 ratio to makes OES and their effect on conversion rate and 5-HMF selectivities was noted for three different time intervals; up to three hours (Fig. 8). All co-solvents increased the yield of product except methanol. Highest fructose conversion was noted with isopropanol yielding 94, 93 and 90% for one, two and three hours respectively. Then the turn is for water, yielding up to 83% 5-HMF. DMSO and EtOH yielded almost the same for one hour processing. Thus, up to 24% yield increment from fructose is obtained by addition of a little isopropanol in reaction mixture. For glucose, a large increment of 53% is noted in the presence of ethanol. The order of reactivity of other co-solvents is methanol > isopropanol > deionized water and dimethyl sulfoxide. The high selectivity of 5-HMF from glucose conversion is due to the stabilization of 1,2-enediol reaction intermediates by ethanol. Thus the rate of mutarotation is increased changing the sugar tautomeric equilibrium in the reaction mixture. More fructose is produced which is then dehydrated readily [35]. Additionally, the dilution effect caused by co-solvent and hydrogen-bonding produced between co-solvent and 5-HMF prevent the 5-HMF to get polymerized [36,37].

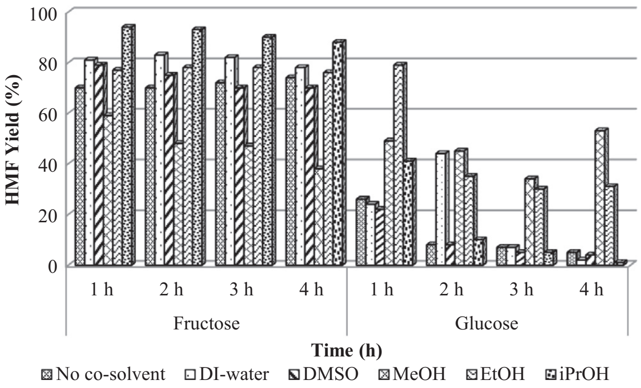

Fig. 8. Effect of co-solvents on 5-HMF production.

3.2.6. Effect of substrate loading

As shown in Fig. 9 with the increase in substrate loading, yields are improved firstly up to 10 wt% loading. Further loading up to 15 wt% caused a little reduction of yield, above which a sharp reduction is observed. This decrease may be due to certain other side reactions at high sugars concentration; excess fructose or glucose present in reaction mixture may polymerize with produced 5-HMF yielding unwanted products [34].

3.3. Conversion of microcrystalline cellulose and real lignocellulosic biomass

After successful conversion of fructose, glucose and process optimization, experimentation was done to convert real cellulose biopolymer (MCC). All ten BAILs as well as twenty BLAILs were totally ineffective for this conversion. A maximum of only 0.01% yield was recorded by IL-3, 7 and 10 when coordinated with $AlCl_3$ (Table S2; SI). All five polar protic and aprotic solvents DI water, MeOH, EtOH, iPrOH and DMSO were then used to make OES with IL-3 and tested for conversion process even at higher reaction times and temperature (up to 150 °C) but no significant result was obtained (Table S3; SI). The only reason we understand for this conversion inhibition is the presence of SO_3H group with butyl side chain of 3-methylpyridinium cation. As reported before SO_3H is best dehydrating group but its saccharification and isomerization efficiencies are not so good [13]. Next, we removed this group and used $[C_4C_1Py]$ cation with best Cl^- anion with and without metal chlorides. As predicted, removal of this group came up with the positive results; 54% 5-HMF yield is obtained with $[C_4C_1Py]CrCl_4$ at 120 °C in only one hour. Same IL was then applied on real

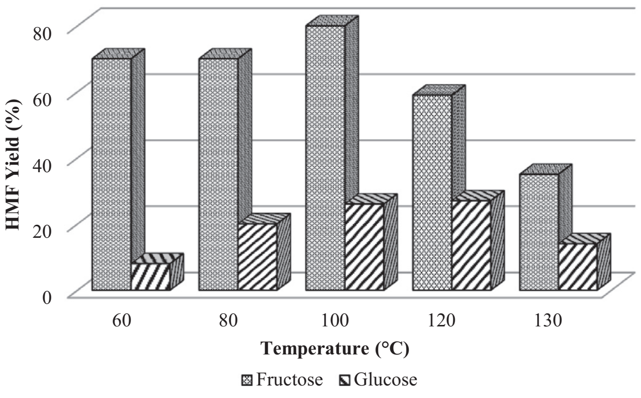

Fig. 7. Effect of temperature on 5-HMF production.

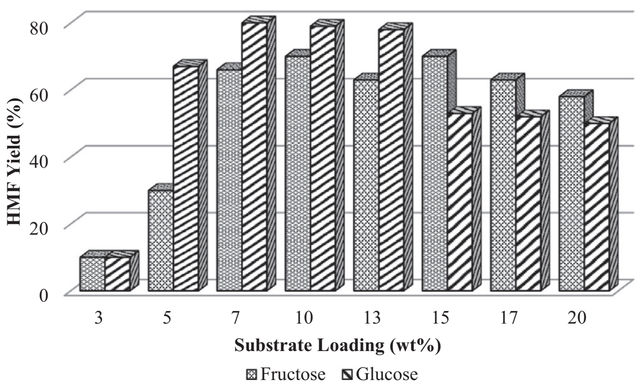

Fig. 9. Effect of substrate loading on 5-HMF production.

Table 3
Synthesis of 5-HMF from MCC and real biomass.

Substrate	IL	5-HMF (%)	TRS (%)	Percentage conversion (%)	5-HMF selectivity (%)
Microcrystalline Cellulose (MCC)	$[C_4C_1Py]Cl$	–	97	–	–
	$[C_4C_1Py]AlCl_4$	–	19	81	0.01
	$[C_4C_1Py]CrCl_4$	54	57	43	70
Wheat Husk (WH)	$[C_4C_1Py]Cl$	–	13	–	–
	$[C_4C_1Py]AlCl_4$	–	15	85	–
	$[C_4C_1Py]CrCl_4$	35	91	97	36

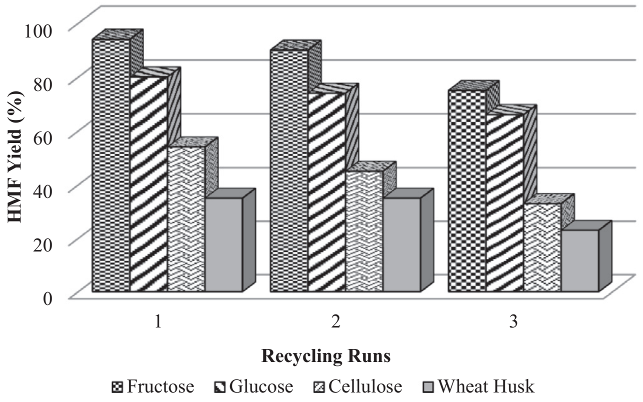

Fig. 10. Recycling studies.

biomass and 35% 5-HMF (based on its original carbohydrate content) is obtained but at 130 °C and 2 h (Table 3).

4. Recycling studies

After product separation from reaction mixture, IL or IL–MCl system was recovered by evaporation of any possible ethyl acetate used for product separation. Percentage recovery of IL is noted to be above 85% and it was used for successive runs by adding fresh saccharide as well as co-solvent each time. A little decrease in efficiency was noted for the third run. Third recovered IL was not able to be used for next run due to its low percent recovery (Fig. 10).

5. Conclusion

A series of 1-butylsulfonic 3-methylpyridinium based ILs with ten different anions were tested for their carbohydrate to 5-HMF conversion efficiencies. From all ten tested anions, *para*-toluene sulfonate and chloride are the most effective for dehydration of fructose; 82 and 76% respective selectivities of 5-HMF are achieved in one hour at 80 °C. Efficiencies of ILs increased > 20% by infusing Lewis acidic character in them. $[C_4SO_3HC_1Py]AlCl_4$ is the most efficient from all produced BLAILs in terms of glucose conversion and product selectivity. Process efficiency for glucose conversion was enhanced yielding 80% 5-HMF by addition of protic organic co-solvents in BLAILs. From all polar protic and aprotic co-solvents tested in this study, best conversion efficiency was observed for polar protic ones may be due to their product stabilization effect caused by hydrogen bonding. The process is highly efficient as high 5-HMF yields; 94% from fructose and 80% from glucose are obtained in only one hour at 80 and 100 °C respectively. Same ILs yielding high from fructose and glucose were ineffective for real biopolymers; cellulose and wheat husk biomass. The reason for this behavior is justified by low isomerization and saccharification power of SO_3H groups united with side chain of cation. Removal of this group came up with 54% cellulosic conversion as well as 35% conversion of wheat husk based on its cellulose and hemicellulose content. UV, HPLC, ^1H NMR and GC–MS approve that 5-HMF is the only product of reaction.

Author contributions

Sadia Naz performed the experimental work and wrote the manuscript. Maliha Uroos and Nawshad Muhammad supervised the work, assured the funding and instrumental analyses for project and validated the analyses data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was financially supported by Higher Education Commission (HEC) Pakistan, under the NRPU Research Grant, project no: 8639/Punjab/NRPU/R&D/HEC/2017 and TDF Research Grant, project no. TDF03-294. School of Chemistry, University of the Punjab is acknowledged for its support towards this project.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.molliq.2021.116523.

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