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# A "Sweet" Biorefinery: Sugar-derived ionic liquids for the pretreatment of lignocellulosic biomass

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ABSTRACT

Sugar-based ionic liquids (ILs) derived from biomass-based cations (choline, betaine) and sugar-derived anions were developed as sustainable pretreatment solvents to advance the concept of self-reliant biorefinery. Cholinium gluconate ([Ch][GlcA]) enabled streamlined one-pot sorghum pretreatment without the need for pH adjustment or washing, while betainium gluconate ([Bet][GlcA]) achieved higher sugar yields, improving overall process efficiency and economics. Both ILs produced hydrolysates fully compatible with microbial fermentation, demonstrating their potential for efficient, simplified biomass conversion. This work positions sugar-based ILs as powerful platforms that unite sustainable chemistry with integrated bioprocessing, marking a pivotal step toward realizing the self-reliant biorefinery.

## 1. Introduction

The concept of a biorefinery, which integrates the production of biofuels, bioenergy, and chemicals from renewable biomass, is central to advancing resource efficiency (Welfle and Röder, 2022; Welfle et al., 2023). However, the intricate and recalcitrant structure of lignocellulosic biomass remains a major obstacle to efficient valorization (Pham et al., 2022; Shrestha et al., 2024). Overcoming this barrier often requires the incorporation of delignification as an additional chemical, physical, mechanical or biological pretreatment step. Among these, chemical pretreatments involving hot water, dilute acids, dilute alkalis, ionic liquids (ILs), organic solvents, have been demonstrated as effective strategies, but they typically require extensive water washing or post-processing, resulting in substantial costs and high energy demands (Li et al., 2010; Mankar et al., 2021; Patel and Shah, 2021; Sai Bharadwaj et al., 2023). ILs, defined as organic salts with melting points below 100 °C, offer a promising alternative (Zhang, 2022). They enable biomass pretreatment under milder conditions and can be tailored through diverse ionic combinations to enhance processing efficiency, owing to their distinctive physicochemical properties such as low vapor pressure, high thermal stability, a wide liquid range, and strong solvation capacity for biopolymers (Hallett and Welton, 2011; Verdía Barbará et al., 2025; Yao et al., 2021). Furthermore, the use of biocompatible ILs facilitate downstream processing and reduce or eliminate the need for water washing or other post-processing steps (Pidatala et al., 2024; Sun et al., 2017; Verdía Barbará et al., 2025; Yao et al., 2021).

While imidazolium and other ions in ILs have been shown to effectively dissolve lignocellulosic biomass (Cruz et al., 2013; Roy and Chundawat, 2023; Tadesse and Luque, 2011), these ions, like most industrial chemicals, are typically derived from petroleum resources. Synthesizing ILs from ions sourced directly from biomass offers a compelling alternative, enabling a self-reliant biorefinery with inherent feedstock availability. This strategy aligns with the closed-loop biorefinery concept proposed by Hulsbosch et al., which utilizes ILs derived from renewable compounds such as sugars from cellulose (Hulsbosch et al., 2016). Such a self-reliant, closed-loop biorefinery provides an economic advantage by leveraging lignocellulosic components to minimize waste through process stream valorization and to maximize resource efficiency (Fig. 1) (Socha et al., 2014). It is also critical for improving the economic sustainability of biorefineries by decoupling

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production from linear resource consumption. We propose that exploiting sugars as fundamental precursors for IL synthesis represents a viable pathway towards a self-reliant biorefinery and constitutes a novel and significant contribution to the field.

This study aims to develop sugar-derived ILs as biocompatible pretreatment solvents for lignocellulosic biomass, offering a potentially more cost-competitive alternative to conventional ILs. Specifically, sugar acids derived from glucose and galactose were utilized as anions to synthesize these cost-effective ILs. We predict that these sugar-derived ILs will enable high fermentable sugar yields from pretreated biomass and may eliminate the need for post-pretreatment pH adjustment and/or IL separation prior to fermentation, thereby providing a pathway to reduced processing costs in biofuel and biochemical production.

Utilizing sugar-derived anions for IL synthesis presents a notably more promising route, requiring fewer synthetic steps compared to transforming sugars into cations (Gaida and Brzęczek-Szafran, 2020). Sugar acids can be obtained by oxidizing sugars such as glucose and galactose, which, in the presence of a base, deprotonate to yield sugar-derived anions. The anions employed in this study include gluconate ([GlcA]$^-$), glucuronate ([GlcU]$^-$), and glucarate ([GlcAA]$^-$) from glucose, and galacturonate ([GalU]$^-$) and galactarate ([GalAA]$^-$) from galactose, as shown in Scheme 1. The cations used, cholinium and betainium, can also be sourced from biomass (Toledo Hijo et al., 2016). The selection of these biomass-derived cations further suggests the potential to source all constituent ions required for IL synthesis within a biorefinery, highlighting the possibility of a fully integrated and self-reliant system. Our findings primarily establish the viability of sugar-derived ILs, marking a crucial step toward biorefinery-integrated production of these valuable pretreatment solvents.

## 2. Experimental

### 2.1. Materials

All chemicals were used as received unless otherwise noted. Deionized water (18 MΩ·cm at 25 °C) was obtained from Purelab Flex (ELGA, Woodridge, IL, USA). Choline hydroxide (46 % in water), sodium hydroxide pellets (≥97 %), ammonium sulfate, dodecane, pentadecane, sulfuric acid (98 %), gluconic acid, glucuronic acid, glucaric acid potassium salt, galacturonic acid, galactaric acid, betaine, and deuterated methanol were purchased from Sigma-Aldrich (St. Louis, MO, USA). Ethanol (200 proof) was obtained from Decon Labs, Inc. (King of Prussia, PA, USA), and sulfuric acid (72 %) from RICCA Chemical Company (Arlington, TX, USA). Bisabolene was purchased from TCI (Portland, OR, USA), while Dowex® 50WX8–200 was sourced from Spectrum Chemical Mfg. Corp. (New Brunswick, NJ, USA). Analytical-grade glucose and xylose standards (Sigma-Aldrich) were used for calibration.

Biomass feedstocks studied here were pine (*Pinus radiata*) and sorghum (*Sorghum bicolor*, donated by Idaho National Labs, Idaho Falls, USA). Biomass samples were dried at 40 °C for 24 h, followed by knife-milling with a 2 mm screen (Thomas-Wiley Model 4, Swedesboro, NJ, USA). Processed biomass was stored in leak-proof bags under dry, cool conditions. Commercial cellulase (Cellic® CTec3) and hemicellulase (Cellic® HTec3) mixtures were obtained from Novozymes North America (Franklinton, NC, USA).

### 2.2. Methods

#### 2.2.1. Synthesis of ILs

Cholinium- and betainium-based ILs were synthesized via acid–base reactions between choline hydroxide (or betaine) and the corresponding sugar acid. Cholinium glucarate was prepared via a two-step synthesis, consisting of glucaric acid formation followed by an acid–base reaction (see the Supplementary Materials).

#### 2.2.2. Characterization of ILs (FT-IR and TGA)

The chemical structures of the synthesized ILs were identified by Fourier transform infrared (FT-IR) spectroscopy using a Bruker VERTEX 70/80 system (Billerica, MA). Data acquisition and analysis were performed using OPUS (version 8.2, build 8, 2, 28 (20,190,310) software. Thermal behavior was evaluated via thermal gravimetric analysis (TGA) using a Mettler Toledo Stare TGA/DSC1 unit (Mettler Toledo, Leicester,

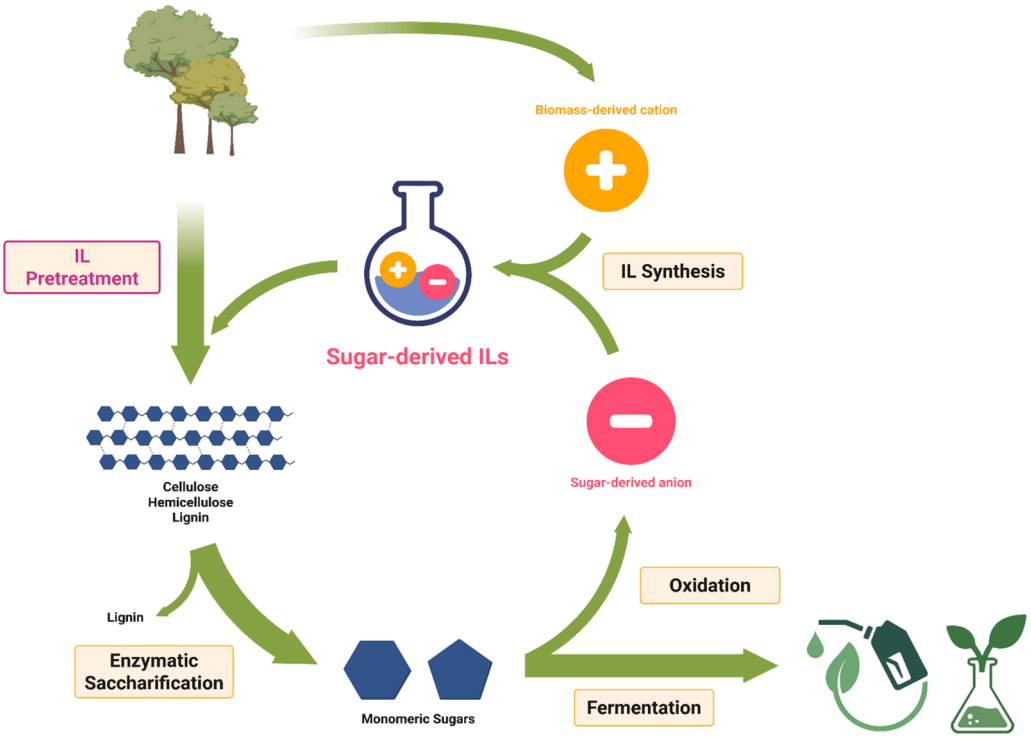
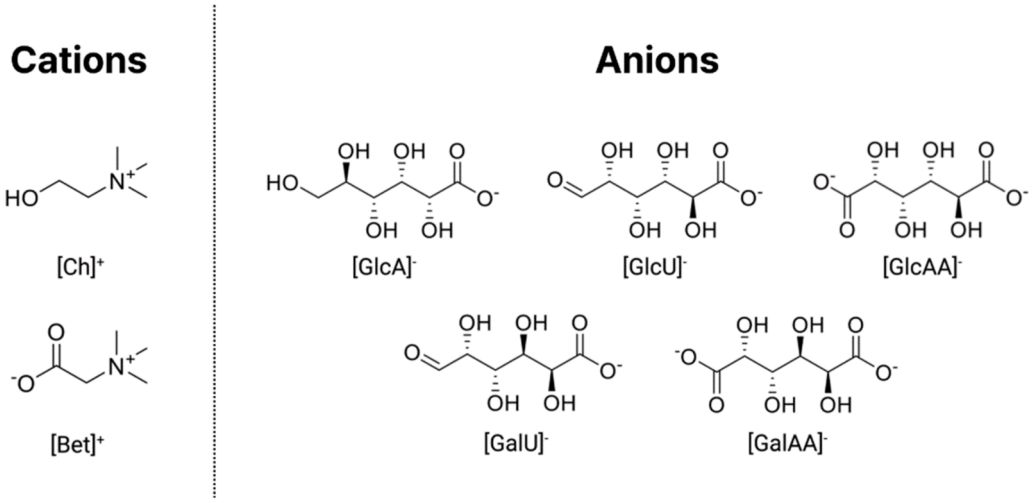



**Fig. 1.** Overview of a "sweet" biorefinery based on sugar-derived ILs.




**Scheme 1.** Structures of cations and anions used in this study. Cations: cholinium ([Ch]$^+$) and betainium ([Bet]$^+$); Anions from glucose: gluconic ([GlcA]$^-$), glucuronic ([GlcU]$^-$), and glucaric acid ([GlcAA]$^-$); Anions from galactose: galacturonic ([GalU]$^-$) and galactaric acid ([GalAA]$^-$).

UK) under nitrogen (50 mL/min). 3–10 mg of samples was loaded into 70 μL crucibles and heated from room temperature to 75 °C at a heating rate of 10 °C/min, maintaining an isotherm at 75 °C for 30 min to remove volatiles. Subsequently, the temperature was increased to 800 °C at a heating rate of 10 °C/min. Data analysis was conducted using STARe Evaluation software.

### 2.2.3. Biomass pretreatment

Pretreatment reactions were performed in duplicate. Biomass (2 mm pine or sorghum), synthesized IL, and DI water were combined in a 2:1:7 ratio (w/w; 20 wt % biomass loading) in 15 mL capped glass pressure tubes. Samples were heated at 140 °C in an oil bath for 3 h. After cooling to room temperature, pH was measured, if necessary, adjusted to 5 using hydrochloric acid or sodium hydroxide as required.

### 2.2.4. Washing method

After pretreatment, samples were removed from the oil bath and allowed to cool. 10 mL DI water was slowly added to the biomass/IL slurry and mixed well. The mixture was transferred to 50 mL Falcon tubes and centrifuged at high speed (4000 rpm) to separate solids and remove any residual IL. The water washed solid was freeze-dried to obtain dried pretreated biomass for further analysis.

### 2.2.5. Enzymatic saccharification

Enzymatic saccharification was performed at 50 °C for 72 h on an Enviro Genie SI-1200 rotator platform (Scientific Industries, Inc., Bohemia, NY, USA) using a 9:1 (v/v) mixture of Cellic® CTec3 and HTec3 at 10 mg protein $g^{-1}$ biomass. Released sugars were analyzed on a Dionex™ ICS-5000+ SP (Thermo-Scientific, Dionex, Sunnyvale, California USA) high-performance anion-exchange chromatograph with pulsed amperometric detection (HPAEC-PAD) as described previously (Mason et al., 2020). A CarboPac PA20 analytical anion exchange column (3 mm x 150 mm; Thermo Fisher Scientific), PA20 guard column (3 mm x 30 mm), and a borate trap was utilized within the HPAEC. Proceeding a 5 min equilibration, the injected sample was eluted using an isocratic gradient of 4 mM NaOH from 0 to 6 min, followed by a linear gradient of 4 mM NaOH to 1 mM NaOH from 6 to 19 min. At 19.1 min, the gradient was increased to 450 mM NaOH to elute the acidic sugars.

### 2.2.6. One-pot pretreatment and saccharification

The one-pot pretreatment and saccharification reactions were performed in duplicate. Biomass (2 mm pine or sorghum), synthesized IL, and DI water were combined in a 2:1:7 ratio (w/w; 20 wt % biomass loading) in 15 mL capped glass pressure tubes. The mixture was heated at 140 °C in an oil bath for 3 h. After cooling to room temperature, pH was measured, if necessary, adjusted to 5 using hydrochloric acid or sodium hydroxide as required. Subsequently, enzymatic saccharification was performed directly without washing steps, under the same conditions described in Section 2.2.5.

### 2.2.7. Compositional analysis

All compositional analysis experiments were conducted in duplicate. Compositional analysis of biomass before and after pretreatment was performed using NREL acid hydrolysis protocols (LAP) LAP-002 and LAP-005 (Sluiter, 2004). Briefly, 200 mg of biomass and 2 mL of 72 % $H_2SO_4$ were incubated at 30 °C while shaking at 200 rpm for 1 h. The solution was diluted to 4 % $H_2SO_4$ with 56 mL of DI water and autoclaved at 121 °C for 1 h. The reaction was quenched by cooling the flasks before removing the solids by filtration. Carbohydrate concentrations were determined from the filtrate using HPLC (Agilent 1260 Infinity, Santa Clara, CA, USA) equipped with a Bio-Rad Aminex HPX-87H column and a refractive index detector, using 4 mM aqueous sulfuric acid as the eluent (0.6 mL $min^{-1}$, 60 °C).

### 2.2.8. Bioconversion

An engineered strain of the oleaginous yeast *Rhodosporidium toruloides* that produces the jet fuel precursor bisabolene, named GB2.0, was used to test the biocompatibility of the generated hydrolysates after pretreatment and saccharification (Kirby et al., 2021). Notably, the ILs were sufficiently diluted in the preceding steps and did not act as a solvent during bioconversion reaction, thus requiring no additional separation or removal processes (Sun et al., 2016, 2017; Xu et al., 2016; Yao et al., 2021). The hydrolysates were supplemented with ammonium sulfate ($(NH_4)_2SO_4$; from a 100x stock solution for a final concentration of 5 g/L) and filtered through 0.45 μm surfactant-free cellulose acetate membranes after adjusting the pH to 7 with concentrated NaOH. Bisabolene production experiments were performed in triplicate by combining 780 μL of the pH-adjusted and filtered hydrolysates with 20 μL of cells obtained from an overnight culture in yeast peptone dextrose medium and 200 μL of a dodecane overlay using 48-well FlowerPlates (Beckman Coulter, United States), covered with sterile AeraSeal films (Excel Scientific, USA). The plates were incubated for 7 days in a humidity-controlled incubator with orbital shaking at 900 rpm. The entire contents of each well were collected in 1.5 mL tubes and the dodecane layer, supernatant, and cells were separated by centrifugation and each fraction was kept at −20 °C until analysis. To measure final optical density at 600 nm using a SpectraMax Plus 384 reader (Molecular Devices, USA), the cell pellets were then resuspended in 800 μL of

water, diluted forty-fold with water, and 100 μL were transferred to 96-well plates.

*2.2.9. Bisabolene analysis*

To quantify bisabolene produced in the flowerplate cultivations, the dodecane overlays obtained at the end of the experiments were diluted in pure dodecane spiked with 40 mg/L of pentadecane, used as an internal standard. The samples were then analyzed by GC–MS using an Agilent Technologies 6890 N system equipped with a 5973-mass selective detector and a DB-5 ms column (30 m x 250 μm x 0.25 μm, Agilent Technologies, USA). 1 μl injections with a splitless setting were used on a GC oven program consisting of 100 °C for 0.75 min, followed by a ramp of 20 °C per min until 300 °C, and held 1 min at 300 °C. Injector and MS quadrupole detector temperatures were 250 °C and 150 °C, respectively. The bisabolene concentrations reported here correspond to the concentrations that would be present in the aqueous phase of the cultures, obtained by dividing the concentrations measured in the dodecane layer by 4. Bisabolene was calculated by integration of the peak area values obtained in selective ion monitoring mode and compared to the areas obtained from a calibration curve made with pure bisabolene.

## 3. Results and discussion

In this study, the pretreatment efficacy of aqueous sugar-based ILs including cholinium gluconate ([Ch][GlcA]), cholinium glucuronate ([Ch][GlcU]), cholinium glucarate ([Ch][GlcAA]), cholinium galacturonate ([Ch][GalU]), cholinium galactarate ([Ch][GalAA]), and betainium gluconate ([Bet][GlcA]) was investigated in terms of sugar release. These sugar-derived ILs were synthesized via an acid-base reaction between the cation or cation precursors (i.e., cholinium hydroxide or betaine) and the respective sugar acids, as detailed in the Supplementary Materials. Sorghum biomass was pretreated in aqueous IL systems at a biomass:IL:water ratio of 2:1:7 (w/w), which corresponds to 10wt % IL in the reaction mixture (see Fig. 2). The reactions were carried out at 140 °C for 3 h in glass pressure tubes, which were selected based on our prior optimization studies with ILs to achieve consistent and effective lignocellulose fractionation (Achinivu et al., 2023; Das et al., 2021; Yao et al., 2021).

First, we investigated the pretreatment efficiency of cholinium-based ILs on sorghum using the post-pretreatment pH and sugar yield. As shown in Fig. 2(a), the pH of the pretreated sorghum for all the tested sugar-derived ILs was close to the desirable range of 4.8–5.5 for optimal saccharification, with [Ch][GlcA] yielding a pH close to this range. This outcome suggests that a separate pH adjustment step may not be required following the pretreatment with sugar-derived ILs. Nevertheless, to better assess these ILs the sugar yield was determined by enzymatic saccharification after adjusting the pH to 5, using a commercial enzyme cocktail (Novozymes Cellic® Ctec3 and Htec3 at a 9:1 v/v ratio). As illustrated in Fig. 2(b), sugar yield varied significantly depending on the sugar-derived anions employed. [Ch][GlcA] was the most effective pretreatment solvent, with 75.3 % glucose and 47.5 % xylose yield. These results demonstrate the strong performance of [Ch][GlcA], and considering that Magurudeniya et al. reported glucose and xylose yields of 80.52 % and 61.68 %, respectively, with [Ch][Lys], the contribution of [GlcA] to pretreatment appears comparable to that of [Lys] (Magurudeniya et al., 2021). In contrast, [Ch][GalAA] resulted in notably lower yields with 30.3 % glucose and 23.2 % xylose. [Ch][GlcU], [Ch][GlcAA], and [Ch][GalU] exhibited intermediate performance levels, yielding 34.1 % glucose and 24.8 xylose for [Ch][GlcU], 35.6 % glucose and 32.8 % xylose for [Ch][GlcAA], and 36.4 % glucose and 29.9 % xylose for [Ch][GalU]. Given the critical role of IL anions in biomass pretreatment (Konan et al., 2024; Pham et al., 2024), the enhanced efficiency observed can be attributed to the gluconate anion. Similar to the other anions tested in this study, gluconate contained multiple hydroxyl groups and a carboxylate group capable of forming hydrogen bonds with cellulose and lignin. Based on the observed sugar release efficacy, we further anticipated that other anions might render enzymes inactive by binding to their active sites. Moreover, the natural origin, biodegradability, and non-toxicity of gluconate strengthen its potential as a sustainable pre-treatment agent (Costa et al., 2015). Notably, no linear relationship was observed between pH and sugar release, suggesting that other factors may play a more significant role.

Given the high performance of [Ch][GlcA], we analyzed the impact of pH adjustment and pretreatment on the sugar yield (Fig. 3). Overall, the one-pot method was more suitable for [Ch][GlcA] pretreatment than the washing method, yielding 51.6 % glucose and 26.7 % xylose. Remarkably, for the one-pot treated biomass, the non-pH-adjusted biomass yielded 80.9 % glucose and 51.8 % xylose, which is comparable to the 75.3 % glucose and 47.5 % xylose obtained from the pH-adjusted biomass. This finding suggests that an additional pH adjustment step is not required for the [Ch][GlcA] pretreatment. Thus, the ability of the [Ch][GlcA] pretreatment to eliminate the need for both pH adjustment and washing underscores the high potential of sugar-derived ILs for streamlined biomass processing.

Furthermore, we extended this investigation to pine pretreatment using [Ch][GlcA] (Fig. 4). The sugar yield of pine (43.2 % glucose and 20.1 % xylose) was significantly lower than that of sorghum (75.3 % glucose and 47.5 % xylose). Softwood, such as pine, generally has a higher lignin content and greater structural recalcitrance than herbaceous biomass, such as sorghum, which can make deconstruction of its

(a)

| IL | pH after pretreatment |
|---|---|
| Cholinium gluconate | 5.68 |
| Cholinium glucuronate | 5.95 |
| Cholinium glucarate | 6.83 |
| Cholinium galacturonate | 5.94 |
| Cholinium galactarate | 6.24 |

(b)

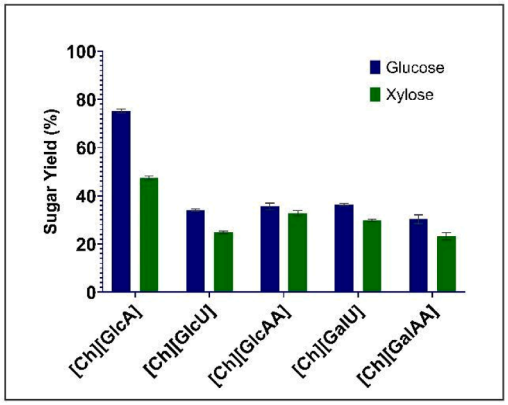



**Fig. 2. (a)** pH and **(b)** Glucose (blue bars) and xylose (green bars) yields after enzymatic hydrolysis of pretreated sorghum with cholinium gluconate ([Ch][GlcA]), cholinium glucuronate ([Ch][GlcU]), cholinium glucarate ([Ch][GlcAA]), cholinium galacturonate ([Ch][GalU]), and cholinium galactarate ([Ch][GalAA]). All ILs were used in aqueous solutions at a 2:1:7 (w/w) ratio of biomass, IL, and water.

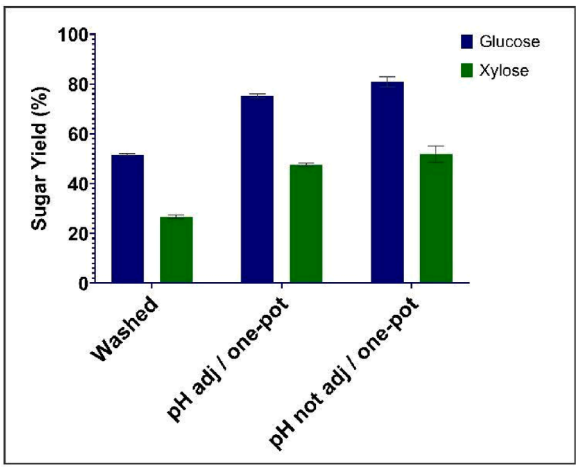



**Fig. 3.** Effect of introducing a washing or pH adjustment step to biomass pretreated with cholinium gluconate ([Ch][GlcA]) on sugar yields of sorghum after enzymatic hydrolysis.

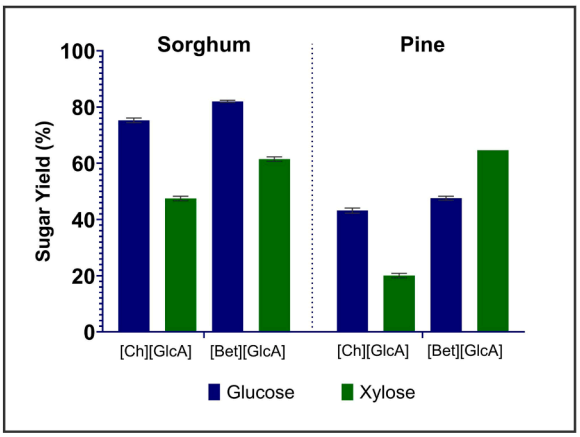



**Fig. 4.** Glucose (blue bars) and xylose (green bars) yields from sorghum and pine biomass pretreated with cholinium gluconate ([Ch][GlcA]) and betainium gluconate ([Bet][GlcA]).

relatively rigid structure more challenging. Fig. 4 also shows the results obtained by synthesizing [Bet][GlcA] using betaine as an alternative cation and subsequently pretreating sorghum and pine. The [Bet][GlcA] pretreatment of sorghum yielded notably high sugar levels, 82.0 % glucose, and 61.5 % xylose. These yields are higher than those achieved with [Ch][GlcA] for sorghum. Pine resulted in 47.6 % glucose and 64.6 % xylose production. Although [Bet][GlcA] led to an increase in glucose yield from pine compared to [Ch][GlcA], it caused a significantly greater increase in xylose yield. These findings suggest that gluconate provides optimum conditions for grassy biomass pretreatment compared to other sugar-derived anions. A deeper understanding of this mechanism through both computational and experimental investigations is required to further optimize pretreatment efficacy for more recalcitrant woody biomass. Furthermore, betaine is considered a potentially more promising material than choline because of its lower cost and higher thermal stability (Table 1), making [Bet][GlcA] a promising cost-effective and effective pretreatment solvent.

For the biocompatibility test, an engineered strain of the yeast *Rhodosporidium toruloides*, capable of producing bisabolene (a biofuel precursor), was cultured in the hydrolysates of sorghum and pine pretreated with [Bet][GlcA]. It is important to highlight that bioconversion was carried out using the hydrolysate without any separation of [Bet][GlcA], thereby establishing it as a biocompatible ionic liquid. As shown

**Table 1**
Thermal gravimetric analysis of various ILs under study.

| IL | %Volatiles | $T_{5\ \%}$ (°C)[a] | $T_{50\ \%}$ (°C)[b] | %Ash |
|---|---|---|---|---|
| Gluconic acid | 6.0 | 141.3 | 297.3 | 11.8 |
| Glucuronic acid | 0.1 | 170.1 | 292.3 | 18.9 |
| Glucaric acid | 1.3 | 128.0 | 219.7 | 17.7 |
| Galacturonic acid | 0.7 | 125.3 | 269.0 | 22.9 |
| [Ch][GlcA] | 10.7 | 161.6 | 222.8 | 12.2 |
| [Ch][GlcU] | 7.6 | 131.9 | 220.3 | 10.3 |
| [Ch][GlcAA] | 0.4 | 180.0 | 210.8 | 10.6 |
| [Ch][GalU] | 0.2 | 175.4 | 218.3 | 10.7 |
| [Ch][GalAA] | 7.2 | 184.3 | 208.4 | 9.7 |
| [Bet][GlcA] | 6.3 | 174.5 | 246.6 | 11.3 |

[a] $T_{5\ \%}$: Temperature value at 5 % mass loss after isothermal step at 75 °C.
[b] $T_{50\ \%}$: Temperature value at 50 % mass loss after isothermal step at 75 °C.

in Fig. 5, robust growth and bisabolene production was confirmed in both sorghum and pine hydrolysates. These results indicate that the hydrolysates obtained from sugar-derived IL pretreatment can serve as a suitable culture medium for *R. toruloides,* and demonstrate the potential for producing valuable substances within the self-reliant biorefinery concept proposed in this study.

## 4. Conclusions

This study establishes sugar-derived ILs, particularly cholinium gluconate ([Ch][GlcA]) and betainium gluconate ([Bet][GlcA]), as effective pretreatment solvents for lignocellulosic biomass. [Ch][GlcA] enabled a streamlined one-pot sorghum pretreatment, yielding 75.3 % glucose and 47.5 % xylose without pH adjustment or water-washing, while [Bet][GlcA] delivered even higher sugar yields (82.0 % glucose and 61.5 % xylose). Importantly, both ILs produced hydrolysates fully compatible with downstream microbial fermentation, underscoring their value for integrated bioprocessing. These findings position sugar-derived ILs as a pivotal platform for efficient, simplified, and biocompatible biomass deconstruction, marking a critical step toward realizing the self-reliant biorefinery.

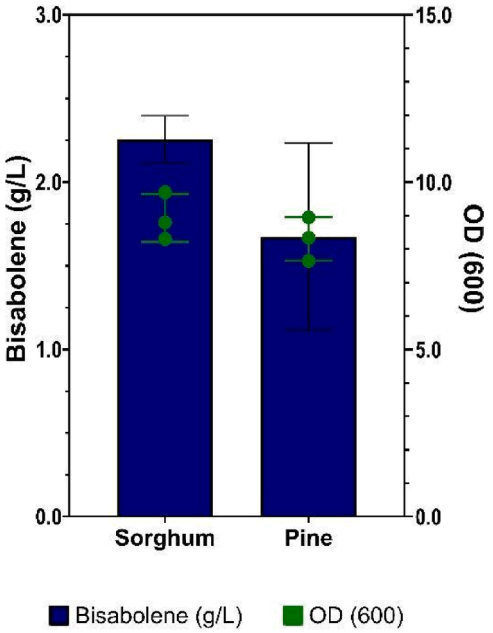



**Fig. 5.** Bisabolene production and cell growth of *R. toruloides* in biomass hydrolysates.

## CRediT authorship contribution statement

**Minsol Kim:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Sara Saldarriaga-Hernandez:** Writing – review & editing, Visualization, Formal analysis. **Alberto Rodriguez:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Danay Carrillo-Nieves:** Writing – review & editing. **Blake A. Simmons:** Writing – review & editing, Visualization, Resources, Funding acquisition. **John M. Gladden:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Hemant Choudhary:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Formal analysis, Data curation, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: BAS reports financial support was provided by U.S. Department of Energy, Office of Science, Biological and Environmental Research. BAS has a financial interest in Illium Technologies, Caribou Biofuels, and Erg Bio. All other authors declare the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. HC is associated with the Editorial Board of Journal of Ionic Liquids.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jil.2025.100184.

## Data availability

No data was used for the research described in the article.

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