Efficient reaction with *in situ* extraction to yield 5-hydroxymethylfurfural and furfural through targeted green solvent selection catalyzed by sulphated zirconia

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Highlights

- Computationally guided solvent screening for cleaner solvent identification
- MIBK and cyclohexanone as ideal recyclable solvent candidates
- Strong Bronsted and Lewis acid sulphated zirconia used for sugar dehydration
- Good yields and selectivity towards furan products realised

1. Introduction

To mitigate the increasing demand of fossil fuels and petrochemicals and their pernicious effects on the environment, valorisation of lignocellulosic biomass unlocks novel opportunities for bio-derived platform chemicals, such as 5-hydroxymethylfurfural (HMF) and furfural (Fur), with a myriad of synthetic upgrading possibilities[1]. Conventionally, their production has been undertaken in acidic single aqueous phase media [2]. However, product selectivity is limited due to rehydration products from HMF, and formation of insoluble humins through self-condensation of both HMF and Fur. Implementation of biphasic reaction with *in situ* extraction can be utilized as a mitigation strategy, for which the COnductor-like Screening MOdel for Real Solvents (COSMO-RS) [3] can assist selecting solvents that allow partitioning of the products. In addition, consideration of the environmental health and safety (EHS) profile of the solvents is important for the development of cleaner operations, for which green solvent selection guides such as CHEM21 show great capability [4]. This work details the identification of suitable green extraction solvents for the reaction with *in situ* extraction of HMF and Fur using a combined methodology with COSMO-RS and solvent selection guides and the subsequent use of heterogeneous sulphated zirconia catalysts for the dehydration of sugars.

2. Methods

Targeted solvent screening of 176 solvents was performed through the use of COSMOthermX (v. 18.0.2), using the BP_TZVP_18 parameterization. The highest ranked solvents were used for experimental determination of the partition coefficient of 1 wt.% of HMF and Fur in aqueous biphasic systems at 25 °C and 50 °C through contacting (Labnet Vortemp 1550) and phase splitting. For HMF and Fur production, three sulphated zirconia catalysts (S1, S2 and S3, supplied by Luxfer MEL) were screened for initial performance, with total NH_3-TPD acidity (μmol/g) of 99.7, 712.5 and 891.5 respectively. Catalyst loading of 5 wt.% with 10 wt.% of aqueous phase of feedstock (glucose, fructose, and xylose) at 140°C for 90 min in an Anton Parr Monowave 400 microwave reactor at 800 rpm. Reaction kinetic experiments were performed in the same setup at temperatures ranging from 120-160°C, from 0-2 h, 0-5 wt.% catalyst loading and 1-20 wt.% substrate loading. Both for partition and reaction experiments, HPLC was used for sample quantification with RI and DAD as detectors.

3. Results and discussion

The COSMO-RS predictions were ranked according to partition coefficients (K_i) and then evaluated using the CHEM21 solvent selection guide for EHS parameters to identify greener extraction solvents.

Figure 1 presents parity plots for HMF and Fur at 323 K, with the method showing some overprediction of K_i. From this, cyclohexanone and MIBK were identified as excellent candidates to bring forward for evaluation of reaction performance for HMF and Fur [5].

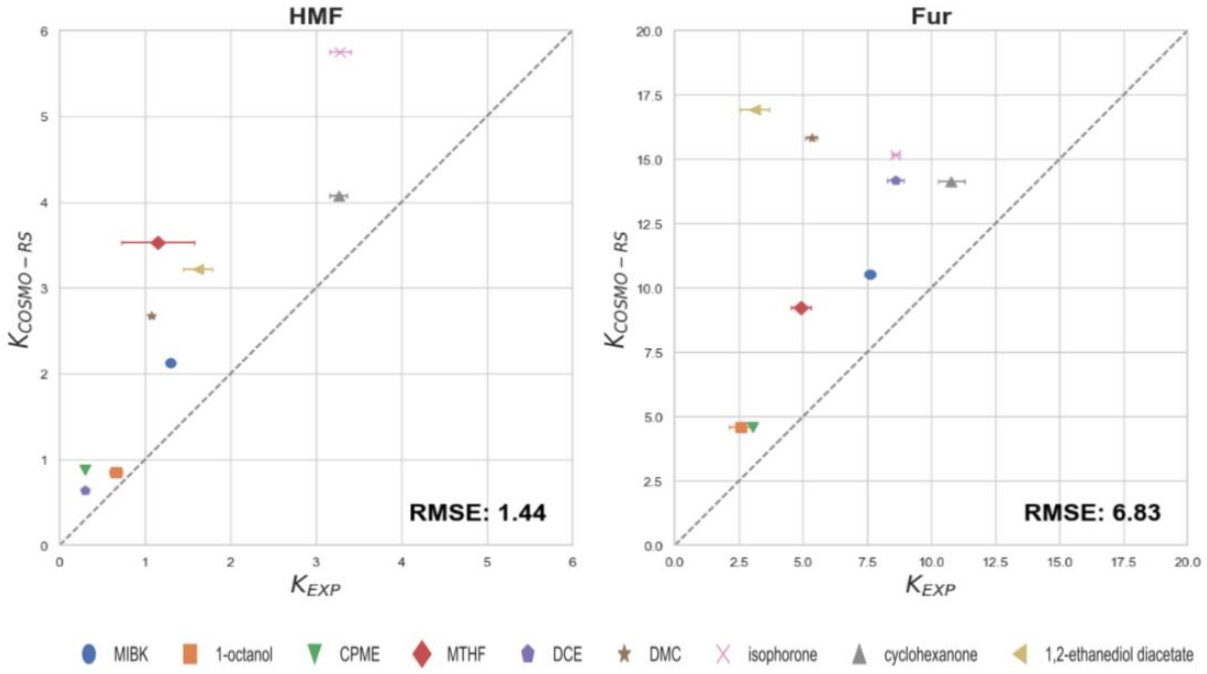

Figure 1:COSMO-RS predicted partitioning vs experimentally determined for HMF and Fur at 323 K.

Catalytic screening indicates the suitability of S2 for the dehydration of fructose and glucose towards HMF with yields exceeding 30% in low substrate concentrations (c.5 wt.%), with S3 towards Fur through xylose dehydration. Additionally, the positive effects of temperature and catalyst loading on the yield and selectivity towards furans products is being investigated.

4. Conclusions

This work provides a general framework for targeted solvent screening and presents cyclohexanone and MIBK as two green extraction solvents for the reaction with *in situ* extraction of HMF and Fur. These solvents exhibited exceptional extraction capabilities and experimental validation lay close to computational predictions. Highlighted solvents were then evaluated for reaction performance with sulphated zirconia catalysts, releasing good yields and selectivity towards furan products at relatively mild conditions c.140°C.

Keywords

Furans, COSMO-RS, green solvents, reaction with *in situ* extraction, process intensification

References

[1] J. Esteban, A.J. Vorholt, W. Leitner, An overview of the biphasic dehydration of sugars to 5-hydroxymethylfurfural and furfural: a rational selection of solvents using COSMO-RS and selection guides, Green Chem. 22(7) (2020) 2097-2128. https://doi.org/10.1039/C9GC04208C.

[2] D. Soukup-Carne, X. Fan, J. Esteban, An overview and analysis of the thermodynamic and kinetic models used in the production of 5-hydroxymethylfurfural and furfural, Chem Eng J 442 (2022) 136313. https://doi.org/https://doi.org/10.1016/j.cej.2022.136313.

[3] A. Klamt, Conductor-like Screening Model for Real Solvents: A New Approach to the Quantitative Calculation of Solvation Phenomena, J Phys Chem 99(7) (1995) 2224-2235. https://doi.org/10.1021/j100007a062.

[4] D. Prat, A. Wells, J. Hayler, H. Sneddon, C.R. McElroy, S. Abou-Shehada, P.J. Dunn, CHEM21 selection guide of classical- and less classical-solvents, Green Chem. 18(1) (2016) 288-296. https://doi.org/10.1039/C5GC01008J.

[5] D. Soukup-Carne, P López-Porfiri, F. Sanchez Bragagnolo, C. Soleo Funari, X. Fan, M. González-Miquel and J. Esteban, Extraction of 5-hydroxymethylfurfural and furfural in aqueous biphasic systems: A COSMO-RS guided approach to greener solvent selection, ACS Sustain. Chem. Eng. Under review (2024).