Minimal viable sugar yield of biomass pretreatment†

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Received September 09 2019; Revised November 19 2019; Accepted November 25 2019; View online January 8, 2020 at Wiley Online Library (wileyonlinelibrary.com); DOI: 10.1002/bbb.2074; Biofuels, Bioprod. Bioref. 14:301–314 (2020)

Abstract: The pretreatment of biomass and the subsequent enzymatic hydrolysis to sugars play an important role in the production of biofuels from lignocellulosic biomass. However, the influence of pretreatment and hydrolysis yields on the production pathway performance of biofuels is rarely researched from the beginning. Moreover, a clear trade-off between economic efficiency and environmental impact exists. Production pathways can be evaluated with reaction network flux analysis (RNFA) (Voll A and Marquardt W, Reaction network flux analysis: Optimization-based evaluation of reaction pathways for biorenewables processing. AIChE J 58(6):1788–1801 (2012)). Utilizing RNFA, this study explores the influence of biomass pretreatment, focusing on changes in biomass composition, fractionation efficiency, and sugar yield after hydrolysis on the production performance of biofuels for several pretreatment concepts and several wood sources. The results show that, for ethanol and ethyl levulinate production, specific fuel costs and carbon loss correlate reciprocally with the yields of pretreatment and hydrolysis. For a constant biofuel output, the main cost driver is the feed stream of biomass, which decreases with an improved overall sugar yield after pretreatment. Furthermore, above a threshold value, specific fuel costs increase strongly with carbon loss. As a result, a minimal yield of 40% carbohydrates from wood seems to be the limit of viable production in the processes that were considered. We therefore developed a facile strategy to assess the performance of pretreatment and hydrolysis in biomass processing © 2020 The Authors. Biofuels, Bioproducts, and Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Supporting information may be found in the online version of this article.

Keywords: biomass pretreatment; biofuel; reaction network flux analysis (RNFA); sugar yield; enzymatic hydrolysis; lignocellulosic biomass

Introduction

Much research has been focused on the production of biofuels from renewables to achieve growth in the biobased economy.1-3 At present, alternative carbon-based fuels can be produced most economically from lignocellulosic biomass.4 The sugars in this feedstock can be made available either by chemical hydrolysis for further catalytic conversion to bioproducts5-7 or by enzymatic hydrolysis for fermentation. The latter option requires pretreatment of the biomass to cleave the composite-like structure of cellulose, hemicellulose, and lignin.

Various process concepts have been suggested for biomass pretreatment, which rely on biological, physical, or chemical principles.8,9 Several variants of chemical pretreatment of lignocellulosic biomasses including softwood, hardwood,
and herbaceous plants, have been demonstrated to be effective: dilute aqueous systems, solvent-enhanced aqueous systems, organic solvent-based pretreatment media, and concentrated ionic liquids. Each of them requires different process technology and yields different fractions of the biomass that have to be processed subsequently.

The overall effectiveness of combined pretreatment and enzymatic hydrolysis is one of the key factors influencing environmental and economic performance of bioethanol production. In this context, effectiveness refers to the total carbohydrate content of the feedstock biomass and the sugar yield and concentration after pretreatment and enzymatic hydrolysis. Notably, some pretreatment concepts are better suited for a specific type of biomass than others. Furthermore, the hydrolysis yield is coupled with the effectiveness of the prior pretreatment step because many factors can reduce hydrolysis enzyme activity down to inhibition. These include lignin that is not completely removed, solvents employed during pretreatment, and the release of soluble inhibiting components and specific degradation products such as aliphatic acids, phenols, sugars, and furan. Reduced enzyme activity leads to decreased sugar yields after hydrolysis. For higher sugar yields, effective pretreatments make cellulose available to the enzymes by breaking up the interwoven structure of lignocellulosic biomass and by decrystallizing cellulose. An extra washing step is also required to remove soluble inhibiting components, even in the case of aqueous pretreatments.

The economics of these processes differ in operational costs. In particular, the costs of enzyme production for the hydrolysis step are estimated to contribute at least 15% or more to the overall costs for the production of bioethanol. Thus, the reduction of enzyme load during hydrolysis represents one key opportunity for a reduction of overall enzyme cost. A lower enzyme load can be enabled by both improving pretreatment and enzyme effectiveness to reach higher sugar yields after hydrolysis. The underlying mechanisms influencing pretreatment and subsequent hydrolysis are not yet completely understood, which makes it very difficult to judge specific pretreatment conditions directly. Thus, the conventional approach explores the viability of one pretreatment concept considering specific biomass composition, pretreatment effectiveness, and enzymatic hydrolysis. However, a general analysis of the effectiveness of a biomass pretreatment and subsequent hydrolysis does not exist. The determination of economically and environmentally viable ranges for the amount of carbohydrates available after pretreatment and hydrolysis represents a first step towards a general understanding of pretreatment.

Early stage evaluation based on material balances allows the assessment of alternative production pathways of a biorefinery. In this context, reaction network flux analysis (RNFA) represents an established tool for the evaluation of alternative pathways in biofuel production considering economic and environmental criteria. In RNFA, a reaction network of various (intermediate) components with possible conversion steps serves as a basis for finding the optimal production pathway of biofuels. However, the influence of different pretreatment and hydrolysis technologies has not yet been considered in detail in RNFA screenings for biofuel production.

In this work, we use RNFA to analyze the impact of pretreatment and hydrolysis yields, and biomass composition, on different conversion pathways with regard to the pretreatment strategy, focusing on chemical pretreatment. We choose two representative biofuel products, ethanol and ethyl levulinate, which feature biotechnological and chemocatalytic conversion and qualify as fuel components for spark-ignition engines.

This article is structured as follows. First, we compile various pathways for pretreatment and enzymatic hydrolysis from the literature in an existing reaction network for the production of ethanol and ethyl levulinate from lignocellulosic biomass. Biofuel production is optimized, minimizing carbon loss and specific fuel cost. Second, we determine the influence of pretreatment and hydrolysis efficiency on the production of a biofuel for beech wood as one specific species of biomass. Third, we evaluate published data on organosolv pretreatment as a well known pretreatment concept to determine the range of carbon loss and fuel cost for one representative pretreatment concept with different species of lignocellulosic biomass. Naturally, numerous combinations of biomass species with different pretreatment technologies are conceivable. However, the data from the literature are limited. Thus, we fourth conduct a generic analysis of pretreatment and hydrolysis yields in combination with changing compositions of biomass to describe the overall relation between carbon loss and fuel cost, and to define the boundaries of economic fuel production.

Methods

Biofuel production in RNFA

Reaction network flux analysis is a screening tool based on a reaction network of various components and conversion
steps. It enables the optimal process pathway to be found at an early stage of process design. It comprises a mass-based analysis and does not include an energetic evaluation. A process pathway screening with RNFA is beneficial if the choice of production pathways is not straightforward (as in the case of ethanol) but, rather, there are several alternative, partially interlinked production pathways without an obvious optimal pathway (as in the case of ethyl levulinate). Figure 1 shows the reaction network for the production of ethanol and ethyl levulinate from biomass, where each arrow represents a reaction from one component, depicted as node, to another component. The network is a sub-network of the one published by Ulonska et al. and comprises only those reactions that are relevant for the production of ethanol and ethyl levulinate via enzymatic hydrolysis. Furthermore, the yields for fermentation of sugars and subsequent downstream processing reactions are kept as in the original publication whereas the yields of reactions R1–R5 for biomass pretreatment and enzymatic hydrolysis as well as the biomass composition are varied.

In particular, reactions R1, R2, and R3 refer to biomass pretreatment for the fractionation of cellulose, hemicellulose, and lignin, respectively. Reactions R1–R3 are not varied independently because they belong to one specific pretreatment experiment and thus they are coupled via mass balances. Nevertheless, we consider the fractionation of the three main components as three separate reactions because each component has individual fractionation yields. Reaction R4 refers to the enzymatic hydrolysis from hemicellulose to xylose and reaction R5 describes the enzymatic hydrolysis of cellulose to glucose.

Stoichiometry and yield data of the individual reactions serve as input for the calculation of stationary mole balances. The output of the biofuel production network is fixed to an energy equivalent of 100 000 t ethanol per year to ensure comparability of the solutions in terms of capacity. Furthermore, RNFA gives cost estimates for the realization of individual pathway designs. For the comparison of biofuels, specific fuel production cost is chosen as an economic criterion and carbon loss as an environmental criterion. To find the optimal fuel production pathway, both criteria should be minimized (Eqn (1)):

$$\min \begin{bmatrix} \text{Fuel cost} \\ \text{Carbon loss} \end{bmatrix}$$

s.t.  Stoichiometry and yield constraints

Fuel cost (feedstock, invest, waste).  \(\text{(1)}\)

Unless otherwise stated, reaction yields and the mathematical formulation of the optimization problem were chosen as in Voll et al. with modifications by Ulonska et al. and König et al. The MINLP optimization problem was solved in GAMS (version number 25.1.1) with the deterministic global solver BARON (version number 18.5.8). The multi-objective optimization problem is converted into a single-objective problem using the \(\epsilon\)-constraint method.
The specific fuel production costs, $C_{\text{spec}}$, are calculated from the total annualized cost in relation to the heating value $\Delta H_{\text{comb,fuel}}$ of the fuel stream $b_{\text{fuel}}$ (Eqn (2)):

$$C_{\text{spec}} = \frac{\text{TIC} + C_{\text{raw}} + C_{\text{waste}}}{b_{\text{fuel}} \cdot \Delta H_{\text{comb,fuel}}}.$$  (2)

With a fixed energy equivalent to be produced, the denominator has the same constant value for the ethanol and ethyl levulinate screenings. Total investment costs (TIC) are calculated from investment costs (IC) corrected for the influence of interest rates and the assumed runtime of the biofuel production facility (cf. Table S1 in the supplementary material, File S1). Here, IC correlates with the number of functional units: for each active reaction (i.e., chosen by the algorithm for the optimal solution) one functional unit is considered in the calculation of IC. However, the number of functional units has been adapted for pretreatment reactions (R1–R3), which take place in one reactor (i.e., one functional unit) as well as hydrolysis reactions (R4, R5), which are also considered to be one functional unit.

Furthermore, the costs for raw material, $C_{\text{raw}}$, and waste, $C_{\text{waste}}$, can be calculated considering the respective streams (Eqns (3) and (4)):

$$C_{\text{raw}} = \sum_{j=1}^{n_{\text{raw}}} f_{\text{raw},j} \cdot M_{\text{raw},j} \cdot P_{\text{raw},j}$$  (3)

$$C_{\text{waste}} = \sum_{j=1}^{n_{\text{waste}}} \left( w_{\text{waste},j} + b_{\text{waste},j} \right) \cdot M_{\text{waste},j} \cdot P_{\text{waste}}$$  (4)

with specific costs $P_{\text{raw},j}$ and molar masses $M_{\text{raw},j}$ for the molar input streams $f_{\text{raw},j}$ and specific costs $P_{\text{waste}}$ and molar masses $M_{\text{waste},j}$ for the waste streams of side-product $w_{\text{waste},j}$ and by-product $b_{\text{waste},j}$ respectively (cf. Table S2 in supplementary material File S1). $n_{\text{raw}}$ refers to the number of feed streams (biomass, hydrogen, water and oxygen) and $n_{\text{waste}}$ refers to the number of waste streams.

Carbon loss (CL) is calculated from the carbon efficiency $\eta^C$ (Eqn (5)):

$$\text{CL} = 1 - \eta^C$$  (5)

where $\eta^C$ refers to the carbon atoms in the fuel stream as a fraction of the carbon atoms in all input streams in the production process of a biofuel (Eqn (6)):

$$\eta^C = \frac{b_{\text{fuel},j} \cdot N_{C,\text{fuel}}}{\sum_{j=1}^{n_{\text{raw}}} f_{\text{raw},j} \cdot N_{C,j}}.$$  (6)

To estimate carbon loss and fuel cost, RNFA requires yield parameters for all reactions as input. The calculation of yields for the pretreatment and hydrolysis steps from literature data is explained in the following section.

### Biomass pretreatment in RNFA

The evaluation of fractionation efficiency during pretreatment is usually carried out with a mass-based analysis in the literature while RNFA is mole-based. Hence, the weight fractions $w_{i,\text{raw}} = m_{i,\text{raw}} / m_{\text{raw}}$ of the three main components, cellulose (c), hemicellulose (hc) and lignin (l), for the native biomass as well as the recovered pretreated biomass are converted to mole fractions $x_{i,\text{raw}} = \left( m_{i,\text{raw}} / M_i \right) / \left( \sum_i \eta^i m_{i,\text{raw}} / M_i \right)$. We assume that the input stream of biomass $m_{\text{raw}}$ consists of the three main components as well as a fraction other which closes the mass balance: $M_{\text{raw}} = \sum_i \eta^i m_{i,\text{raw}} + m_{\text{other}}$ $i \in \{c, hc, l\}$. The molar masses of the monomer units are taken as: $M_c = 162.14 \text{ g mol}^{-1}$, $M_{hc} = 150.13 \text{ g mol}^{-1}$, $M_l = 180.2 \text{ g mol}^{-1}$. As an assumption, we also use the molar mass of lignin for the fraction other, and include $x_{\text{other}}$ in the lignin mole fraction because, in the context of RNFA, neither can be utilized in further processing steps.

Figure 2 gives a schematic overview of the streams that we consider for the analysis of pretreatment efficiencies. After the pretreatment step p, the biomass is split into a recovered (r) solid fraction and a fraction that is solubilized (s) in the pretreatment liquid, whereas both fractions consist of cellulose (c), hemicellulose (hc), and lignin (l):

$$m_{\text{raw}} = m_r + m_s$$  (7)

$$m_p = m_{c,p} + m_{hc,p} + m_{l,p} \quad p \in \{s, r\}$$  (8)

The amount and composition of the recovered and the solubilized fraction (Eqns (7) and (8)) are used to calculate...
the molar fractionation yields $y_{i,p}$ of the pretreatment step $p$ for the three main components:

$$y_{i,p} = \left( \frac{m_{i,p}}{M_i} \right) / \left( \frac{m_{raw,p}}{M_i} \right) \quad \forall i, p \in \{c, hc, l\}, p \in \{s, r\}. \quad (9)$$

For the pretreatment and hydrolysis reactions, the molar- and weight-based fractionation yields for each component are equivalent because the molar masses in Eqn (9) cancel out. The composition of both recovered fraction and solubilized fraction are not available in all evaluated references. We therefore consider only the highest given yield for each component ($c$, $hc$, $l$) for either the solubilized or the recovered stream and allocate this yield to reactions R1, R2, and R3: $y_i = \max(y_{ir}, y_{is})$. Mostly, we used the yield of the recovered fraction of cellulose and the yield of the solubilized fraction of hemicellulose.

Usually, the non-converted biomass components are burned for heat integration, so they are not considered as waste streams causing additional disposal costs in Eqn (4).

Hydrolysis yields $y_{x,h}$ and $y_{g,h}$ are calculated for reaction R4 from the amount of xylose ($x$) after the hydrolysis step $h$ as a fraction of the available hemicellulose after the pretreatment step and for reaction R5 from glucose ($g$) as a fraction of the available cellulose, respectively:

$$y_{x,h} = \left( \frac{m_{x,h}}{M_x} \right) / \left( \frac{m_{hc,p}}{M_{hc}} \right) \quad p \in \{s, r\} \quad (10)$$

$$y_{g,h} = \left( \frac{m_{g,h}}{M_g} \right) / \left( \frac{m_{c,p}}{M_c} \right) \quad p \in \{s, r\}. \quad (11)$$

We do not account for differences in enzymatic conversion rates for glucose and xylose.

The benchmark for the comparison of different pretreatment concepts is the ideal fractionation of biomass combined with an ideal enzymatic hydrolysis (i.e., the yields of reaction R1–R5 are equal to 1). This means that, after pretreatment and enzymatic hydrolysis, all the carbohydrates of the respective input stream of biomass are available for further conversion to the selected biofuels.

The first analysis considers six different pretreatment concepts using only beech wood as feedstock: dilute acid (DA), \(^{10}\) ionic liquid (IL), \(^{13}\) Kraft, \(^{39}\) liquid hot water (LHW), \(^{40}\) a one-phasic organosolv (OS) \(^{44}\) and a two-phasic organosolv (Organocat (OC)) \(^{21,42}\) (cf. supplementary material File S1 for selection of references). The composition of beech wood for the benchmark is set to the composition with the minimal reported lignin fraction. Table 1 gives an overview of the compositions and yields of the considered references.

The second analysis focuses on organosolv pretreatment as one specific pretreatment concept fractionating different types of biomass: sugarcane bagasse, \(^{43–45}\) softwoods spruce \(^{41,45,46}\), pine, \(^{12,47,48}\) and hardwoods tulip tree (TT), \(^{49}\) elm, \(^{48}\) and beech. \(^{41}\) Analogous to the first analysis, the composition for the benchmark is set to the composition with the smallest reported lignin fraction. Table 2 gives an overview of the biomass composition and yields of the references considered for organosolv pretreatment.

The third analysis aims at characterizing the general influence of biomass composition and pretreatment on the production of biofuels. To this end, the input biomass composition and yields for pretreatment and hydrolysis do not rely on literature data but are systematically varied. The influence of a changing lignin content is investigated from 0 to 0.85. Cellulose and hemicellulose content are changed accordingly, considering a fixed $c/hc$ ratio of 1.7, corresponding to the ratio of average cellulose content (0.4257) to average hemicellulose content (0.2526) of the investigated literature data. Furthermore, the influence of a changing cellulose to hemicellulose ratio at a fixed $c/hc$ ratio of 1.7, corresponding to the ratio of average cellulose content (0.4257) to average hemicellulose content (0.2526) of the investigated literature data. Furthermore, the influence of a changing cellulose to hemicellulose ratio at a fixed $c/hc$ ratio of 1.7, corresponding to the ratio of average cellulose content (0.4257) to average hemicellulose content (0.2526) of the investigated literature data. Furthermore, the influence of a changing cellulose to hemicellulose ratio at a fixed $c/hc$ ratio of 1.7, corresponding to the ratio of average cellulose content (0.4257) to average hemicellulose content (0.2526) of the investigated literature data.
Table 2. Molar compositions and yields considered for the screening of organosolv pretreatment based on a variety of biomasses in comparison to the benchmark of ideal pretreatment. (a) Benchmark and softwoods spruce and pine, (b) sugarcane bagasse and hardwoods tulip tree (TT), elm, and beech.

| Ref. | Ideal | Spruce | Pine |
|------|-------|--------|------|
| x_c  | 0.48  | 0.42   | 0.46 |
| x_HC | 0.28  | 0.19   | 0.24 |
| x_I  | 0.24  | 0.4    | 0.4  |
| y_c  | 1     | 0.69   | 1    |
| y_HC | 1     | 0.9    | 1    |
| y_I  | 1     | 0.7    | 0.71 |
| y_X  | 1     | 1      | 1    |
| y_g  | 1     | 0.29   | 0.7  |

| Sugarcane bagasse | TT | Elm | Beech |
|-------------------|----|-----|-------|
| x_c               | 0.42| 0.42| 0.43  |
| x_HC              | 0.25| 0.3  | 0.30  |
| x_I               | 0.32| 0.28| 0.24  |
| y_c               | 0.86| 0.85| 0.83  |
| y_HC              | 0.97| 0.9  | 0.76  |
| y_I               | 0.88| 0.84| 0.56  |
| y_X               | 1   | 1    | 1     |
| y_g               | 1   | 0.96 | 0.21  |

Results and discussion

Analysis of pretreatment of beech wood

Figure 3 shows the results of RNFA for beech wood. To distinguish between the influence of pretreatment efficiency and the influence of hydrolysis efficiency, we consider the reported fractionation yields in combination with (a) the reported hydrolysis yields (i.e., yields of reactions R1–R5 as calculated from literature) and (b) with ideal hydrolysis yields (i.e., yields of reactions R1–R3 as calculated from literature and R4 = R5 = 1). Carbon loss is plotted as a function of the specific fuel costs for the production of ethanol and ethyl levulinate.

Overall, the results show a singleton Pareto front for ethanol (i.e., the minima of carbon loss and fuel cost coincide for each analyzed pretreatment concept) due to only one direct production route from xylose and glucose each (R6 and R7 in Fig. 1), which are both active for all analyses. In contrast, there is a noticeable trade-off between minimal fuel cost and minimal carbon loss for ethyl levulinate. The production of ethyl levulinate offers several optional production pathways that differ in terms of overall yield and number of process steps. For the analyses presented, the production pathways R11–R12–R26 starting from glucose and R15–R16–R25 starting from xylose in different combinations with the fermentation of sugars (R6 and R7) are the only active pathways (cf. Table S4 and S5 in supplementary material File S1). The minimization of fuel costs leads to a lower number of active pathways (i.e., fewer functional units), which results in significantly reduced investment costs (cf. Ulonska et al.31). For all screened pretreatment concepts, the xylose pathway is inactive for the point of minimal ethyl levulinate fuel costs because it has lower yields than the glucose pathway. At the same time, carbon loss is not minimal because less material is converted in comparison to the other points. Conversely, for the minimization of carbon loss, the xylose pathway is active, leading to higher fuel costs.

From a production cost perspective, ethanol is cheaper than ethyl levulinate for all considered pretreatment technologies mainly due to the lower number of reactions in the production network and because, in most cases, a slightly higher amount of costly biomass is required for the production of ethyl levulinate.

From an environmental perspective, the results are substantially different. The production of ethanol shows...
higher carbon losses than the production of ethyl levulinate for all pretreatment variants. Besides losses due to yield constraints of the individual reactions, one molecule of CO₂ is released (i.e., one carbon atom lost) for each molecule of ethanol produced during fermentation. For the production of ethanol, all available sugar molecules are fermented, whereas for the production of ethyl levulinate only a fraction of the sugars is fermented to produce ethanol for reactions R25 and R26. This leads to the overall higher carbon loss for ethanol in comparison to ethyl levulinate.

Figure 3(b) shows the screening results considering the reported fractionation yields combined with ideal hydrolysis yields. In the context of RNFA, ideal hydrolysis means that, during the hydrolysis step, all sugars that are present after pretreatment are made available (i.e., maximum yield) for further processing independent of the specific reaction conditions (e.g., substrate loadings, time of hydrolysis). In comparison to the benchmark, specific fuel costs increase only slightly when evaluating the influence of pretreatment on the production of one type of biofuel. In contrast, the carbon loss ranges approximately from 0.6 to 0.8 for ethanol and from slightly below 0.5 to almost 0.75 for ethyl levulinate. Kraft pretreatment has almost the same values of carbon loss and fuel costs as the benchmark for both biofuels.

The remaining investigated pretreatment concepts exhibit increased carbon loss with a narrow ranking: liquid hot water > ionic liquid > dilute acid > organosolv > Organocat. With ideal hydrolysis, the different performances of the pretreatment concepts arise from variations in the fractionation yields for cellulose and hemicellulose in combination with the slightly varied composition of the raw material.

Considering reported yields for both fractionation and hydrolysis clearly influences the screening of pretreatment concepts as can be seen from a comparison of Fig. 3(a) and (b). As a result, the ranking of pretreatment concepts in Fig. 3(a) is as follows: Kraft > ionic liquid > dilute acid > organosolv > liquid hot water > Organocat. In particular, the results for liquid hot water and Organocat pretreatment differ. Incomplete hydrolysis leads to an increase of carbon loss of approximately 0.1 in both cases and an estimated fuel cost difference of up to 10 USD GJ⁻¹, which renders them unfavorable for realization in a biorefinery compared to the other pretreatment concepts. For the remaining pretreatment technologies that were investigated, the inclusion of experimental hydrolysis yields leads to minor changes in carbon loss and fuel cost. Enzymatic hydrolysis is thus close to or at the optimum for these references. Whether this ranking is generally true or depends on the combination of pretreatment and type of biomass (the specific chosen references) should be validated by a more extensive comparison including several references for each.
pretreatment concept. However, such an analysis is beyond the scope of this publication. Furthermore, the overall costs for the pretreatment and hydrolysis step are similar in RNFA due to the same number of functional units and disregard of solvent costs, which might not be true for a more detailed process design. Generally, the pretreatment and hydrolysis step are capital intensive. In addition, solvent-intensive pretreatment concepts such as the organosolv process often show a poor economic performance due to high costs for solvent recycling. The estimated price might thus be too low. Nevertheless, a comparison of different pretreatment concepts shows that the costs for reactors and associated costs, such as catalyst recovery, often level out. This results in little differences in projected economic performances. Hence, the analysis that is presented allows a simple comparison of pretreatment concepts based on the individual fractionation efficiency and hydrolysis performance.

In addition to the benchmark, we include a pathway screening with minimum achievable carbon loss (min CL) in Fig. 3(a). Here, all yields of the reaction network equal 1. Both carbon loss and fuel costs of the min CL screening are close to the benchmark, which shows that the established yields of the downstream processing reactions are near to the optimum. In conclusion, fractionation yields are the crucial yields in most cases, whereas the effectiveness of enzymatic hydrolysis presents a bottleneck only in two cases.

Overall, the estimated range of fuel cost for the analyzed process variants seems reasonable when comparing to published data. The 2018 average price for bioethanol is 27 USD GJ$^{-1}$, which shows that RNFA rather underestimates real fuel prices. Ethyl levulinate costs have been estimated to 12 USD GJ$^{-1}$, which is at the lower end of RNFA estimates. Nevertheless, not all of the screened pretreatment concepts would be realized in a biorefinery context due to economically more attractive markets. For example, the prices for hardwood Kraft pulp vary between 500 and 800 USD t$^{-1}$. In comparison, a fuel price of 10 USD GJ$^{-1}$ corresponds to a price of 277 USD t$^{-1}$. It is thus more profitable to sell Kraft pretreated pulp directly instead of converting it further to a biofuel. Combusting the biomass would lead to a price of 0.05 USD kg$^{-1}$/19.51 MJ kg$^{-1}$, which marks a lower limit for profitable biofuel production. All presented concepts surpass this lower limit.

The analysis of the pretreatment concepts with beech wood verifies that pretreatment and hydrolysis have a significant influence on the process performance of biofuel production. Reduced sugar yields due to incomplete fractionation and hydrolysis increase both carbon loss and fuel cost. Furthermore, an evaluation of a pretreatment concept is only meaningful in combination with the respective hydrolysis yields but pretreatment yields dominate the performance of both steps (cf. Alvira et al. and Ding et al.). Likewise, the composition of the biomass and the corresponding yield after pretreatment is of particular interest.

**Analysis of organosolv pretreatment**

To generalize the performance of pretreatment and to further determine the influence of varying biomass input streams, a second analysis is carried out with organosolv pretreatment for different feedstocks. The results of RNFA are presented in Fig. 4.

For the same reasons as in the first analysis, there is only one point for each ethanol pretreatment that is considered but a Pareto front for ethyl levulinate. Again, ethyl levulinate shows higher specific fuel costs at a lower carbon loss when comparing the individual experiments. The benchmark in the analysis of beech wood differs from the benchmark in this analysis due to the different compositions of biomass that were used for the calculation of the benchmarks (cf. Table 1 and Table 2). The pathways, which are active for the production of ethyl levulinate based on organosolv pretreatment, are similar to the pathways, which are active for ethyl levulinate produced from beech wood (i.e., glucose pathway R11–R12–R26 and xylose pathway R15–R16–R25 in combination with fermentation of sugars R6 and R7, cf. Table S6 and Table S7 in supplementary material). Again, the glucose pathway is favored for the point of minimal cost with two exceptions: one process based on spruce wood (ideal pretreatment and hydrolysis) and one process based on pine wood (ideal pretreatment and hydrolysis).

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**Figure 4.** Screening results for the production of ethanol (filled symbols) and ethyl levulinate (striped symbols) based on organosolv pretreatment. Hardwood feed streams are marked with a square, softwood with a triangle, and non-woody biomass is marked with a diamond. The symbols correspond to the symbols given in Table 2.
to the low cellulose hydrolysis yields in these two experiments, the xylose pathway is appropriate for the production of ethyl levulinate at minimal costs. The low sugar yields after hydrolysis also result in these two experiments being ranked last in the organosolv screening.

Overall, the organosolv screening results cover a large range of fuel cost and carbon losses, similar to the results in Fig. 3(a). A ranking of the screening results in terms of the biomass type is not straightforward. In all experiments based on sugarcane bagasse carbon loss is in the range of around 0.7, at the same time achieving relatively low fuel costs. This leads to the conclusion that non-woody biomass is favorable for organosolv pretreatment. The results for biofuel production from hardwood show a larger span of carbon loss from approximately 0.7 to 0.85 with a respective increase in fuel costs. The results for softwood cover an even larger span of carbon loss and fuel cost. Moreover, both the best and the worst results are calculated for spruce wood in this analysis. As the composition of the investigated spruce samples is rather similar in both references, the main reasons for this deviation are the reported fractionation and hydrolysis yields, presumably due to different experimental parameters (composition of pretreatment liquid, temperature and pretreatment time). Verification of this hypothesis and comparison of such parameters would require another variable: the severity of a pretreatment concept, which is, however, beyond the scope of this publication.

The correlation between carbon loss and specific fuel costs shows two regimes. Below a carbon loss of approximately 0.8, fuel costs increase only marginally with an increase in carbon loss. On the other hand, the increase in fuel cost is disproportionately high for a carbon loss above approximately 0.8. Even small increases in carbon loss lead to a high increase in fuel cost in this second regime. This turning point is more pronounced for ethanol than for ethyl levulinate. Thus, to avoid high fuel costs, one should aim for pretreatment strategies resulting in a carbon loss below 0.8.

Based on this analysis, it is unclear if and how a certain biomass composition in combination with individual fractionation and hydrolysis yields results in a low carbon loss. To examine the underlying correlation between specific fuel costs and carbon loss in more detail, an analysis based on representative biomass compositions and yields is presented in the next section.

Analysis of minimal viable sugar yield

The aim of this analysis is to detect boundaries of economically favorable production of biofuels based on the total carbohydrate yield after hydrolysis. To this end, values for biomass composition and the yields for pretreatment and hydrolysis were varied in plausible ranges between 0 and 1 based on the considered references. The hypothetical data should enable to analyze the behavior observed with real biomass of different composition.

Figure 5(a) shows the results for the representative analysis of varying lignin content with a fixed cellulose / hemicellulose ratio and average pretreatment and hydrolysis yields. For comparison, screenings based on average lignin content are also included for ethanol and ethyl levulinate. The points increase in steps of 5% from 0% lignin to 85% lignin. The results follow a clear curve from low carbon loss with low fuel costs at low lignin contents to a carbon loss above 0.9 and high fuel costs at high lignin contents. Moreover, the Pareto front for the ethyl levulinate results has a similar shape for most points. The Pareto front narrows only towards a higher lignin content (i.e., a lower range of carbon loss and fuel cost for the results of a specific lignin content). The same production pathways are active for the different points of the Pareto front, due to the constant ratio of cellulose to hemicellulose. In conclusion, a low lignin content of the feedstock biomass is clearly beneficial for a low carbon loss and low fuel costs. This is in line with earlier studies showing that the production of biofuels derived from lignin is economically not feasible.56 A low lignin content not only implies an increased fraction of carbohydrates that can be converted effectively to biofuels, but also diminishes the inhibition potential of enzymes during hydrolysis.

Figure 5(b) shows the screening results for a variation of c/hc ratio at a fixed average lignin content with average pretreatment and hydrolysis yields. For ethanol production with a low cellulose content (c/hc = 0.1) there is a Pareto front because, for the point with minimal costs, hydrolysis of cellulose and fermentation of glucose is inactive. With increasing c/hc ratio, carbon loss and fuel cost decrease slightly. A high cellulose content is therefore beneficial for the production of ethanol (cf. Alvira et al. and Tao et al.).9,15 For ethyl levulinate, the shape of the Pareto front changes with changing c/hc ratio and the individual points of the different Pareto fronts partly overlap. Due to the possibility of choosing different pathways for the production of ethyl levulinate, a change in c/hc ratio can be balanced both in terms of carbon loss and fuel cost.

Figure 5(c) shows the results of the organosolv screening. The points and symbols are the same as the ones used in Fig. 4 but the legend indicates the amount of sugar which is available for biofuel production after pretreatment and hydrolysis. The overall sugar yield can be calculated from the composition of the biomass multiplied with the pretreatment and hydrolysis yields: $w_{\text{sugar}} = w_c \cdot y_c + w_{hc} \cdot y_{hc} + w_{yc} \cdot y_{yc}$. Clearly,
the overall ranking of the screening results correlates with the amount of sugar that is available after hydrolysis.

To deduce the connection between carbon loss, fuel cost and the available sugars, the RNFA equations are analyzed in more detail in the following. For the present analysis, only the feed stream of biomass $f_{\text{raw,bio}}$ is relevant for the calculation of carbon loss from Eqns (5) and (6) since the other feed streams (hydrogen, water and oxygen) do not contain any carbon atoms. As RNFA considers a fixed fuel production, the nominator of Eqn (6) is constant for a specific type of biofuel whereas the denominator changes depending on the magnitude of the biomass input stream.

In conclusion, the denominator can be reformulated to:

$$\sum_{j=1}^{n_{\text{raw}}} f_{\text{raw,j}} N_{C,j} = f_{\text{raw,bio}} N_{C,bio}$$

Here, $N_{C,bio}$ varies marginally between 6.5 and 7.5 depending on the individual composition and, therefore, the carbon loss is mainly proportional to the input stream of biomass according to the relation in Eqn (12):

$$\text{CL} \propto \left(1 - \text{const.} / f_{\text{raw,bio}}\right).$$

(12)

When evaluating the influences on specific fuel costs, the biomass costs are at least one order of magnitude larger than...
costs for auxiliaries and waste. Investment costs are in the same order of magnitude as biomass costs but are similar for the different pretreatment concepts due to the same production pathways. In conclusion, changes in specific fuel costs $C_{\text{spec}}$ are mainly caused by a changing quantity of biomass required for the production of the specified fuel equivalent depending on the effectiveness of the individual pretreatment concepts:

$$C_{\text{spec}} \propto f_{\text{raw_biomass}}.$$  

Combining Eqs (12) and (13) results in the overall relation between carbon loss and fuel cost:

$$\text{CL} \propto \left(1 - \text{const} / C_{\text{spec}}\right).$$  

This equation reflects the observed carbon loss and cost correlation (exemplarily sketched for ethanol in Fig. 5(c)). For a carbon loss approaching its upper limit of 1, the fuel costs increase strongly. When the carbon loss approaches small values, there is a minimum value for the specific fuel costs, which is determined by the constant. This constant in Eqn (14) is process specific and is not further determined for this analysis.

The analysis shows that, to reach a fixed fuel equivalent as output, a certain amount of convertible carbohydrates is required depending on the yields of active production pathways. Thus, the biomass input stream $f_{\text{raw_biomass}}$ increases to reach the required amount of carbohydrates when either the amount of cellulose or hemicellulose in the biomass is low or fractionation and hydrolysis yields are low. On the other hand, high yields or a high carbohydrate content in the biomass feedstock lead to a reduction of the input biomass stream. The overall sugar yield that results from biomass composition, pretreatment, and hydrolysis yields thus determines the quantity of the biomass input stream. Carbon loss and fuel cost are directly connected to the overall sugar yield after hydrolysis. The strongly increasing fuel costs above a carbon loss of 0.8 correspond to an overall sugar yield of approximately $400 g_{\text{sugar}} kg_{\text{biomass}}^{-1}$ (approximate inflection point of sketched curve in Fig. 5(c)), which can be regarded as a minimum overall sugar yield for an economically beneficial production of biofuels. This value can serve as an indicator to judge the yield of biomass pretreatment strategies in general.

This study emphasizes that pretreatment is an integral part of the biomass conversion process. It should therefore be considered with specific pretreatment and hydrolysis yields in combination with further conversion and downstream processing from the very early stages of process development for the production of biofuels. Furthermore, only a complete analysis of raw material, solid recovery, and hydrolysis yields from one experiment allows the correct evaluation of mass balances (cf. Dale and Ong) and the determination of whether a combination of pretreatment and subsequent enzymatic hydrolysis exceeds the above suggested minimum overall sugar yield of $400 g_{\text{sugar}} kg_{\text{biomass}}^{-1}$ for a specific feedstock biomass.

Lignocellulosic biomasses with a low lignin content (i.e., high carbohydrate content) can be pretreated with mild conditions that might not extract all available carbohydrates (i.e., low yields for reactions $R_1$–$R_5$) but still exceed the minimum sugar yield. On the other hand, a high lignin content (i.e., low carbohydrate content) makes pretreatment difficult because, in this case, pretreatment conditions are required that make available most of the cellulose and hemicellulose fraction and also enable high hydrolysis yields. This logic has to be anticipated when choosing a hypothetical site that offers only a specific feedstock, as well as during process development for a specific feedstock.

Strictly speaking, the suggested minimum sugar yield for an economically beneficial production of biofuels has to be validated for each individual process concept during detailed process design. Nevertheless, this lower limit helps in the quick evaluation of research results and in the decision regarding whether a pretreatment concept can be feasible or not.

**Conclusion**

The present study evaluates the influence of various biomass pretreatment concepts and enzymatic hydrolysis on the production process performance of the biofuels ethanol and ethyl levulinate. Reaction network flux analysis is used to screen processes at early stage to minimize fuel cost and carbon loss. Fuel cost and carbon loss strongly depend on pretreatment and hydrolysis yields as the inclusion of literature data for the pretreatment of beech wood and organosolv-based pretreatments of a variety of feedstock biomass species reveals. The comparison of ethanol and ethyl levulinate shows that there can be a trade-off between carbon loss and specific fuel costs. In case of ethanol, the trade-off is insignificant due to the direct, short production pathways from both xylose and glucose. In case of ethyl levulinate, different combinations of production pathways are selected for minimal costs versus minimal carbon loss.

Furthermore, a detailed analysis shows that carbon loss correlates with the reciprocal value of specific fuel costs or total sugar yield. In particular, a carbon loss below approximately 80% corresponds with the pretreatment strategies with a high economic potential. This threshold
in carbon loss coincides with an overall sugar yield of approximately 400 g total carbohydrates per kg of lignocellulosic biomass. To classify a pretreatment as economically beneficial, this critical carbohydrate output should be exceeded either by a large (accessible) carbohydrate content of the feedstock biomass or by efficient fractionation and hydrolysis.

**Acknowledgements**

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy – Exzellenzcluster 2186 ‘The Fuel Science Centre’. This work was performed as part of the Cluster of Excellence ‘Tailor-Made Fuels from Biomass’, which is funded by the Excellence Initiative by the German federal and state governments to promote science and research at German universities.

We thank Hannah Ingendale for assistance with the literature research.

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