HEMICELLULOSE STUDY – PHASE 2

Executive summary

16 March 2018

This study is commissioned by
the Biobased Circular Business Platform.

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CONTENT

OBJECTIVES

The key objective of this study was to provide RVO.nl and the Biobased Circular Business platform with a solid understanding on hemicellulose valorisation in the coming decade

1. *Which intermediates/products can be produced from the three hemicellulose fractions in focus?*
2. *What combination of feedstock, processing technology and purification is needed to produce the intermediates / products, as well as what can be indicated about the desired scale of production?*
3. *What should be the “Hemicellulose paying capability” of these intermediates/products for them to be competitive with current fossil and bio-based alternatives?*
4. *What insight can be given into expected technical or market disruptions having an impact on the economics of the studied processes in the coming 10 years?*

STUDY APPROACH

This executive summary highlights the objectives, study approach and key findings of the Hemicellulose valorisation study completed in early 2018

- The study was carried out by Pöyry Management Consulting in close cooperation with RVO.nl and the Biobased Circular Business platform between January and March 2018
- The analysis was structured in four phases covering (A) Markets, (B) Technologies, (C) Production economics, and (D) Conclusions and implications
  - The first phase included listing of intermediate products that can be produced from the three types of hemicellulose – pure xylose, hydrolysed hemicellulose and hemicellulose in polymeric form – on commercial scale by 2030 (ref. table on the right). The intermediate chemicals were then pre-screened in terms of market size and development status.
  - In the second phase, Pöyry described the known conversion routes from hemicellulose to the 9 pre-screened intermediate chemicals. These routes were then evaluated by jointly agreed criteria such as price level, process complexity, feedstock requirements and yield.
  - Techno-economic analysis, including block diagrams, indicative mass and energy balances, production costs and profitability indicators, was then carried out for three selected products: xylitol, glycols and furfural. All technical modelling was based on public information such as news articles, conference presentations, scientific papers and patents.
  - The final step summarised the key findings of the economic analysis but also reflected the results in wider context of hemicellulose valorisation. In addition, the final step included a discussion on expected technical or market disruptions that may have an impact on production economics in the coming ten years.

PÖYRY

STEP A PRE-SCREENING

Listing of intermediate products that can be produced from the three types of hemicellulose in commercial scale by 2030 on basis of Phase 1 results. Products will be pre-screened in terms of:

- *Market size*
- *Development status*

- Pöyry conducted a pre-screening (next page) based on the work carried out by Wageningen University and publicly available information
  - *Some products from Wageningen's results were excluded e.g. due to early development phase (TRL) or because they were derived from other building blocks on the list e.g. furfuryl alcohol from furfural or polyethylene from ethanol*
  - *Some TRLs are listed with a question mark because the role of hemicellulose in these technologies is not clear*
- The chemicals that passed pre-screening based on TRL and market size are highlighted in green colour
- Feedback from the BCB working group was taken into account in the final selection

EVALUATION CRITERIA FOR STEP B

1. *Estimated price level / current market price*
2. *Complexity of the process*
3. *Feedstock requirement*
4. *Yield*
5. *Competing conversion routes from other bio-based of fossil feedstocks*

10% 1. Price

- **1** < 500 EUR/t
- **2** 500-1 000 EUR/t
- **3** 1 000 – 1 500 EUR/t
- **4** 1 500 – 2 000 EUR/t
- **5** > 2 000 EUR/t

10% 2. Complexity

- **1** Complex process
- **3** Medium
- **5** Straight forward

20% 3. Feedstock requirements

- **1** Hemicellulose composition has high impact on product split / productivity
- **3** Almost all feedstocks ok, inhibitors and impurities have minimal impact on process
- **5** Almost all feedstocks ok, small impact on product split / productivity

30% 4. Conversion yield, w/w%

- **1** < 10%
- **2** 10 – 30%
- **3** 30 – 50%
- **4** 50 – 70%
- **5** > 70%

30% 5. Competing routes

- **1** Multiple routes from bio-based and fossil feedstocks already in operation
- **5** Significant advantages over other bio-based / fossil routes (e.g. no other routes exist)

CONVERSION ROUTES FOR TECHNO-ECONOMIC ANALYSIS

C
Economics

Techno-economic evaluation of 2-3 most promising conversion routes from Step analysis, including:

- *Scale of production*
- *Block diagrams*
- *Indicative mass and energy balances*
- *Feedstock requirements*
- *OPEX*
- *Profitability and hemicellulose paying capability*
- *Sensitivity analyses*

Note:

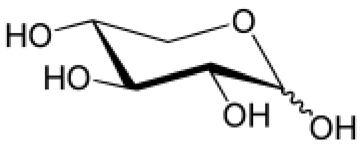
- For the technical modelling: At times, the available information has been very limited and Pöyry has had to make multiple assumptions based on expert opinions of Pöyry's biorefining engineers

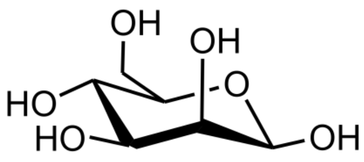
METHODOLOGY FOR PROFITABILITY

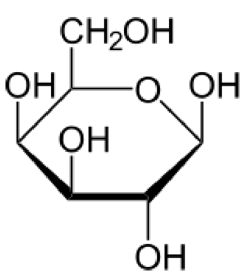
Capital charges, taxes and fixed capital re-investment are not included in cash flow calculations

Year	% of TCI	% of production	Cash flow/a
1	30	0	- 0.3 * TCI
2	60	0	- 0.6 * TCI
3	10	50	- 0.1 * TCI + 0.5 * (Sales revenue – Variable operating costs) – Fixed operating costs
4	0	70	0.7 * (Sales revenue – Variable operating costs) – Fixed operating costs
5	0	90	0.9 * (Sales revenue – Variable operating costs) – Fixed operating costs
6	0	100	Sales revenue – Operating costs
7	0	100	Sales revenue – Operating costs
8	0	100	Sales revenue – Operating costs
9	0	100	Sales revenue – Operating costs
10	0	100	Sales revenue – Operating costs
11	0	100	Sales revenue – Operating costs
12	0	100	Sales revenue – Operating costs
13	0	100	Sales revenue – Operating costs
14	0	100	Sales revenue – Operating costs
15	0	100	Sales revenue – Operating costs
16	0	100	Sales revenue – Operating costs
17	0	100	Sales revenue – Operating costs

CONCLUSIONS AND IMPLICATIONS ON HEMICELLULOSE VALORIZATION







1. **Hydrolysis is key**
   Almost all the studied products which can be produced in commercial scale by 2030 are based on hydrolyzed hemicellulose

2. **Hemicellulose composition matters**
   Hemicellulose composition, particularly C5/C6 sugar distribution, has a significant impact on production economics

3. **No generic answers for pretreatment**
   Pretreatment needs and challenges are specific to each feedstock and processing technology

4. **Xylitol and glycol seem promising**
   Studied xylitol and glycol technologies indicate attractive production economics compared with conventional production processes

5. **Integration is necessary**
   Processes utilising hemicellulose hydrolysates should be integrated to the source of sugars

6. **Disruption potential exists with cost reduction**
   Novel processing routes have the potential to disrupt specific chemical markets should there be a significant decrease in production costs

1 ALMOST ALL STUDIED PRODUCTS ARE BASED ON HYDROLYZED HEMICELLULOSE

- Hemicellulose structures are broken down to monomeric and oligomeric sugars in biomass fractionation
- Out of the 20 intermediate products studied in the pre-screening stage of this project, only 5 are based on a polymeric form of hemicellulose, typically referred to as hemicellulose oligomers, and only xylitol is known to benefit from pure xylose feedstock
- Furfural production is able to utilise both monomeric and oligomeric hemicellulose sugars
- With the exception of xylooligosachharides, the technology readiness levels of the intermediates using hemicellulose oligomers are significantly below other screened intermediates

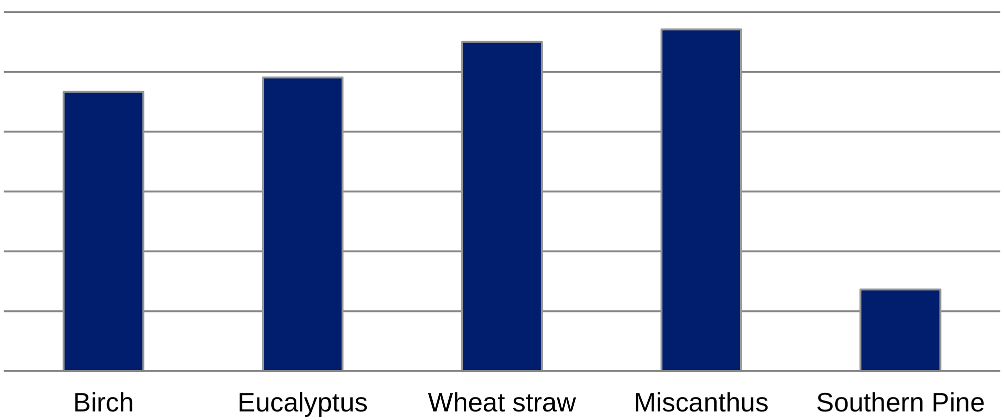
Feedstock	Product	TRL
Hydrolyzed hemicellulose	MEG	5-6
Hydrolyzed hemicellulose	MPG	5-6
Hydrolyzed hemicellulose	EtOH	8
Hydrolyzed hemicellulose	Isobutanol	5
Hydrolyzed hemicellulose	Furfural	7
Hydrolyzed hemicellulose	Mixed hydrocarbons	3-4
Hydrolyzed hemicellulose	n-BuOH	8
Hydrolyzed hemicellulose	Acetone	8
Hydrolyzed hemicellulose	Acetic acid	5-6
Hydrolyzed hemicellulose	Levulinic acid	6-7
Hydrolyzed hemicellulose	Itaconic acid	6-7
Hydrolyzed hemicellulose	Lactic acid	5
Hydrolyzed hemicellulose	Single-cell proteins	7
Hydrolyzed hemicellulose	Formic acid	6-7
Hyd. hemicellulose / pure xylose	Xylitol	9
Hemicellulose in polymeric form	Glucomannan hydrogels	2-4
Hemicellulose in polymeric form	Glucomannan coatings	2-4
Hemicellulose in polymeric form	Xylan barrier films	5-6
Hemicellulose in polymeric form	Xylooligosaccharides (XOS)	9
Hemicellulose in polymeric form	Galactoglucomannan	2-4

2

HEMICELLULOSE COMPOSITION HAS A GREAT IMPACT ON PRODUCTION ECONOMICS

	Spruce[1]	Pine[1]	Poplar[1]	Beech[1]	Birch	Miscanthus[1]	Wheat straw
Arabinose, C5	0.7	1.7	0	0.7	2	1.3	2
Xylose, C5	4.7	5	11.7	19	21	18.1	23
Mannose, C6	9.9	11.9	2.3	19	3	0.1	0
Galactose, C6	1.8	1.4	0.4	1.4	1	0.4	1
Glucose, C6	n/a	n/a	n/a	n/a	2	n/a	1
Total hemicellulosic sugars	16.7	20	14.5	21-28	29	19.9	26

Sales revenue of combined xylitol and glycols production with different feedstocks, MEUR/a



- The composition of the hemicellulose, particularly the C5/C6 sugar distribution, is critical for production yields and process economics in most of the studied cases
- **XOS, xylitol** and **furfural** processes benefit from as high xylose content as possible, and thus feedstock such as **miscanthus, wheat straw**, **birch** and **poplar** would be preferred for these intermediates
- **Softwood hemicelluloses** are most suitable for e.g. **MEG and ethanol processes** which favour high C6 sugar content
- ABE fermentation and single-cell protein processes are able to utilise both C5 and C6 sugars, but typically C6 sugars results in higher yields

[1]*Source: Hemicellulose study – Phase I, Wageningen University*

3 PRETREATMENT NEEDS AND CHALLENGES ARE SPECIFIC TO EACH FEEDSTOCK AND PROCESSING TECHNOLOGY

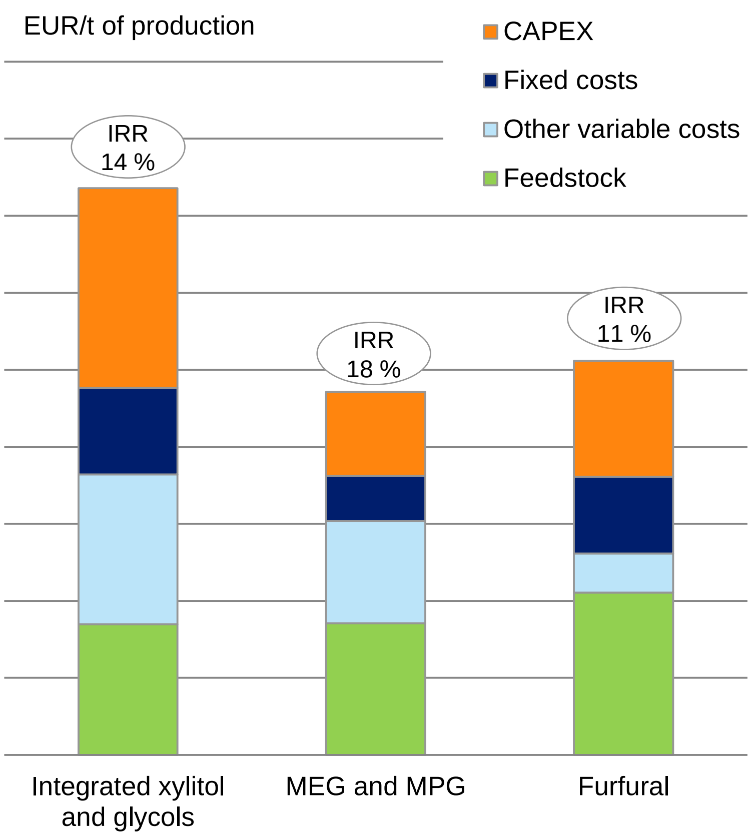
- Hemicellulose pretreatment needs cannot be generalised based on feedstock and product, instead, each processing technology is likely to have specific inhibitors which need to be removed from the feedstock
- Very few commercial processes can afford to require absolutely pure hemicellulosic sugars due to high purification costs. E.g. industrial scale simulated moving bed chromatography is always an option to separate individual sugar components but costs can be prohibitive.
- Lignin is an example of an impurity which should be removed in all the studied hemicellulose routes
- Most studied processes require hydrolysate sugars in monomeric form. Enzymes can then be added to either a separate hydrolysis step or, in the case of ethanol for instance, to the fermentation
- Hemicellulose valorisation and pretreatment concepts are likely to see significant technical advancements in the coming ten years as the processes for bio-based chemical production are becoming more flexible and technologies more mature

GUIDELINES FOR HEMICELLULOSE PRETREATMENT

- Pretreatment needs and challenges are specific to each feedstock and processing technology
- Catalysts and micro-organisms typically have specific inhibitors. It is important to identify these components as early in process development as possible and design the pretreatment concept to target these specific impurities
- Typical pretreatment options include e.g. activated carbon, ion exchange or chelating agents
- Pretreatment optimisation should be carried out in close integration with the entire downstream processing
- 10% sugar content in the hydrolysate stream is sufficient in most processes. Concentration of the sugar hydrolysate is beneficial e.g. in all glycol processes, but it should be noted that most pretreament options require dilute sugar streams

4 STUDIED XYLITOL AND GLYCOL TECHNOLOGIES INDICATE ATTRACTIVE PRODUCTION ECONOMICS

Total production costs

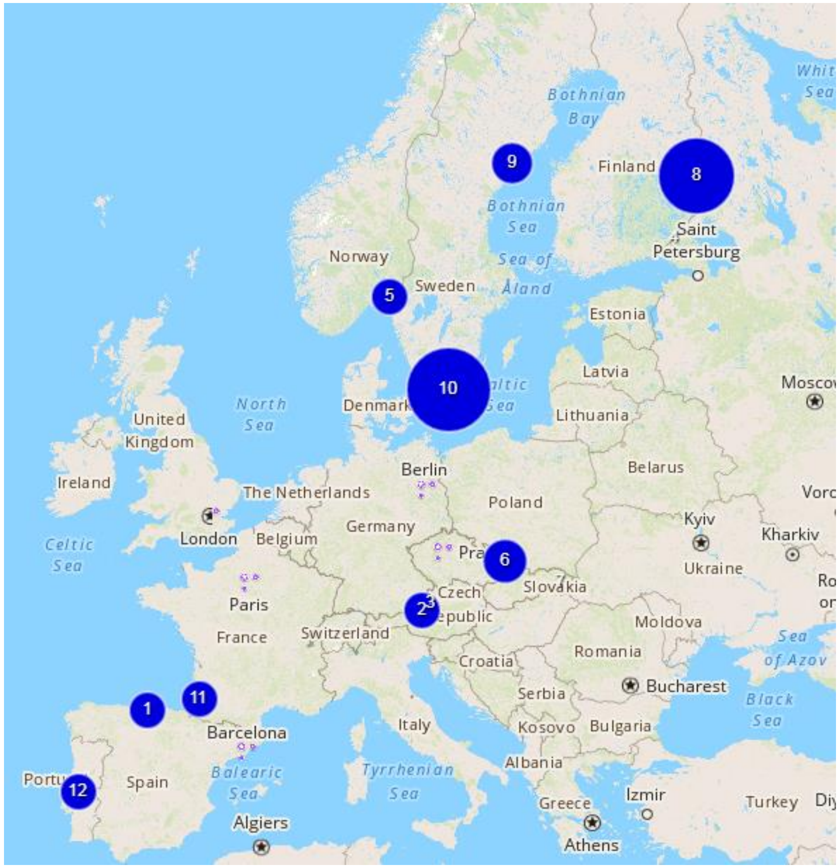


- Techno-economic modelling indicates attractive internal rates of return, IRR, for both S2G integrated xylitol/glycols technology and Haldor Topsoe's MEG/MPG process, 14 % and 18 % respectively
- However, neither of these processes have yet been demonstrated in commercial scale on any feedstock, and thus, there are still many uncertainties and unknowns why these results should be considered indicative
- There have been a number of announcements on chemical / sugar projects based on lignocellulosic feedstock from e.g. Comet Biorefining, UPM and Origin Materials. Learnings from these flagship projects, new cellulosic ethanol investments and biomass fractionation piloting units, e.g. Avantium's Zambezi, will surely benefit also hemicellulose valorisation on the next 5-10 year horizon

5 PROCESSES UTILISING HEMICELLULOSE HYDROLYSATES SHOULD TO BE INTEGRATED TO THE SOURCE OF SUGARS

- Due to the dilute nature of the hemicellulose streams, hemicellulose utilisation should be integrated to the source of sugars, which may be e.g. a dissolving pulp mill, cellulosic ethanol unit or other lignocellulosic biorefinery such as bio-based chemical production
- In order to maximise the benefits of economies of scale, namely related to CAPEX, personnel and other fixed costs, capacities of glycols cases modelled in this study are of the higher end
- The volumes used in the modelling correspond to the hydrolysate sugars obtained from a 200-300 kt/a dissolving pulp mill using birch wood
  - European dissolving pulp capacities range from 65 to 300kt/a
- As a reference, the hemicellulose hydrolysate from 100 000 m3/a cellulosic ethanol plant contains around 40 kt/a of dry sugars
  - Separation of hemicellulosic sugars from cellulosic ethanol production reduces ethanol output significantly compared to integrated C5/C6 fermentation

Operating dissolving pulp mills in Europe



6 NOVEL PROCESSING ROUTES HAVE THE POTENTIAL TO DISRUPT SPECIFIC CHEMICAL MARKETS SHOULD THERE BE A SIGNIFICANT DECREASE IN PRODUCTION COSTS

Market outlook for the studied chemicals

STRONG MARKET GROWTH or SPECIFIC DEMAND FOR BIO-BASED ALTERNATIVES
- Ethanol
- Monoethylene glycol
- Monopropylene glycol
- Single-cell proteins

COST PROHIBITIVE MARKETS
- Xylitol
- Itaconic acid
- Levulinic acid

OVERCAPACITY
- Acetic acid
- Furfural

LARGE COMMODITIES WITH LIMITED INTEREST IN BIO-BASED ALTERNATIVES
- Acetone
- Formic acid

HEALTHY ANNUAL GROWTH
- XOS
- Lactic acid
- Isobutanol
- n-Butanol
- Mixed hydrocarbons

UNDEVELOPED MARKETS
- Glucomannan hydrogels
- Galactoglucomannan
- Glucomannan coatings
- Xylan barrier films

- The studied intermediates can be categorised into six segments based on their market outlook:
  - Chemicals with strong market growth or demand for bio-based alternatives
  - Chemicals with healthy annual growth
  - Cost prohibitive markets, where reduction in production costs could open up a wide variety of new end-uses and demand volume
  - Large commodity chemicals with stable market outlook
  - Markets with overcapacity, which can be challenging for new entrants
  - Chemicals with undeveloped markets
- Although in the case of xylitol, itaconic acid and levulinic acid, reduced production costs could be a tipping point for new applications, it should be noted that building a completely new market demand is likely to take min. 5-10 years
  - E.g. the cases of PLA bioplastic or Stevia sweetener

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