Knowledge and data repository provided to EU knowledge and stakeholder platforms

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Summary

This report represents Deliverable 7.4 and is based on Task 7.5, which aims to evaluate generated knowledge within UNRAVEL for its potential to be shared with the relevant EU knowledge and stakeholder platforms. The report describes how UNRAVEL makes the generated knowledge and data available to EU stakeholder platforms and the knowledge community (in all relevant project areas: overall biorefinery concept, pre-treatment, fractionation, application, sustainability and impact assessment), and shares it by means of a project knowledge repository.

Basis for the repository are selected formats for knowledge transfer, such as summary reports in non-technical language (further referred to as factsheets), strategy papers (by means of Policy Briefs), publications etc. All documents are proactively shared with representatives of EU platforms and stakeholder communities (among them biomass associations, research institutes and research alliances). In addition, the documents are widely made accessible in the project knowledge repository via https://www.unravel-bbi.eu/fact-sheets, which is promoted by social media. It should be noted that knowledge and data covered by intellectual property rights are excluded from the public documents and will be used for exploitation purposes.

Analysis of the best approach and suitable target groups/contacts for curation and sharing of knowledge started early in the project (around M12). Direct knowledge exchange additionally has been and will be performed during UNRAVEL at conferences and via direct communication. These activities have been further described in deliverable report D7.3 1st stakeholder engagement events and results' evaluation report (submitted on the 28th February 2021). The specific task of policy input by means of strategy papers and policy briefs will be further described in the separate deliverable report D7.5 Policy brief and strategy papers with recommendations for policy making (due date is the 30th April 2022), complementing this report D7.4.

In order to spread the knowledge among the scientific audience, data underlying the scientific papers that are published as part of UNRAVEL, were or will be made publicly available as part of the publication in a public repository (e.g. OpenAire, Zenodo etc.).

Data of the lignocellulosic profiles of 25 biomass samples that have been candidates for conversion and valorisation in the UNRAVEL project have been made available in a public and open access database by partner Celignis, who were responsible for analysing the samples. The database can be accessed via the UNRAVEL website and has been promoted via social media.

Contents

1. Introduction

Preservation and transfer of UNRAVEL expertise is essential for securing the successful development of a bioeconomy that is based on lignocellulosic feedstock, downstream processing and product development that prove to be ecologically and economically sustainable. Knowledge exchange is key for the UNRAVEL project as our findings can support different stakeholders over the whole value chain of biomass supply to bio-based products and product compounds. For example: our results of the Life Cycle Analysis which cover the entire value chain from biomass to final product are relevant for different parties, including the forestry and agricultural sectors (key biomass suppliers), the construction and wood chemistry sectors (as targeted end users), the knowledge community (as adopters), environmental NGOs (representing the civil society) and policy makers (using newly generated knowledge and robust data as evidence for future policy making and strategy development). Therefore a project data repository is built, which includes scientific publications, non-technical reports (factsheets), policy briefs, informative video material etc. and is accessible via www.unravel-bbi.eu.

Selection of suitable target stakeholders for curation and sharing of knowledge started early in the project (around M12). Direct knowledge exchange additionally has been and will be performed during UNRAVEL at conferences and via direct communication. These activities have been further described in deliverable report D7.3 1st stakeholder engagement events and results' evaluation report (submitted on the 28th February 2021). The specific task of policy input by means of strategy papers and policy briefs will be further described in the separate deliverable report D7.5 Policy brief and strategy papers with recommendations for policy making (due date is the 30th April 2022), complementing this report D7.4.

By November 2021, selected knowledge and data gained in work package 2-6 has been summarized and converted into two factsheets, which are at the core of this deliverable as they target a general, non-scientific audience and can be found as Annexes to this report. The factsheets are shared with platforms and stakeholders that are predominantly related to the bioeconomy, biomass, biorefinery, and EU sustainability strategies and policies, such as the EU Green Deal.

Directly targeting European stakeholder groups and established knowledge communities supports spreading knowledge and data generated in research and innovation initiatives among various stakeholders and helps to make the UNRAVEL data accessible and understandable outside the scientific community. The factsheets are also openly accessible through the UNRAVEL website as part of the project knowledge repository.

Part of the UNRAVEL dissemination, communication and exploitation strategy is to promote the data among and beyond the scientific community as openly and widely as possible. Therefore, relevant data will be uploaded in relevant scientific databases, which are related to biomass composition and wood chemistry where relevant.

2. Overview of factsheets

TNO and Eurida evaluated the knowledge generated within the first 42 months of UNRAVEL, also with regard to the protection of intellectual property for exploitation. Eurida analysed the EU stakeholder groups that are key to the integration of newly generated knowledge and data in future concepts and strategies. The selected knowledge so far has been summarized and converted into two fact sheets, which form the core of this deliverable.

Factsheet 1 addresses the general UNRAVEL concept of a cascading, mild organosolv lignocellulosic biorefinery, factsheet 2 the processing of complex lignocellulosic biomass and mixed feedstocks from forestry and agriculture.

More factsheets are planned to be developed until the end of the project (May 2022), among them one on key applications for the UNRAVEL lignin, one on promising valorisation paths for C5/C6 sugars and extractives from the combined pre-extraction and fractionation process (ELEANOR/FABIOLA), one on selection of sustainable feedstocks for lignocellulosic biorefinery and one on circularity aspects of an UNRAVEL cascading biorefinery.

All fact sheets are compiled and technical language is translated into non-expert language in collaboration with the project partners that generate the knowledge and data.

The major objectives of the factsheets are:

(1) Raise awareness of key stakeholders towards the potential of an efficient lignocellulosic biorefinery and lignin as compound for a range of high value products to replace fossil resources. This could support the decarbonisation for example of the construction and chemical sectors and become a possible area of economic growth with Europe in the lead.
(2) Provide facts and knowledge and to highlight the potential of forestry and agricultural residues as sustainable biomass, and to support future concepts and practices in biomass selection, allocation and supply chains.
(3) Emphasise the possible impacts, positive and negative, that industrial lignocellulosic biorefinery may have on the environment.

Table 1 provides an overview of the fact sheets that have been compiled as part of the UNRAVEL knowledge exploitation strategy, including those that are already in planning. Each table entry describes the key topics that are covered in the factsheets and the respective target groups for its distribution. The factsheets will be sent directly to members and contacts within these target groups as electronic documents.

The reach of the factsheets is extended by making them openly accessible through the UNRAVEL website, which will be promoted via social media. All interested parties can assess this project knowledge repository at via www.unravel-bbi.eu, which, over the next six months, will also be extended to scientific publications, policy briefs, informative video material and infographics. All important results and knowledge generated by UNRAVEL are preserved and made available for scientists, experts and non-experts, covering different backgrounds and fields of activity.

3. Overview of data shared in scientific databases

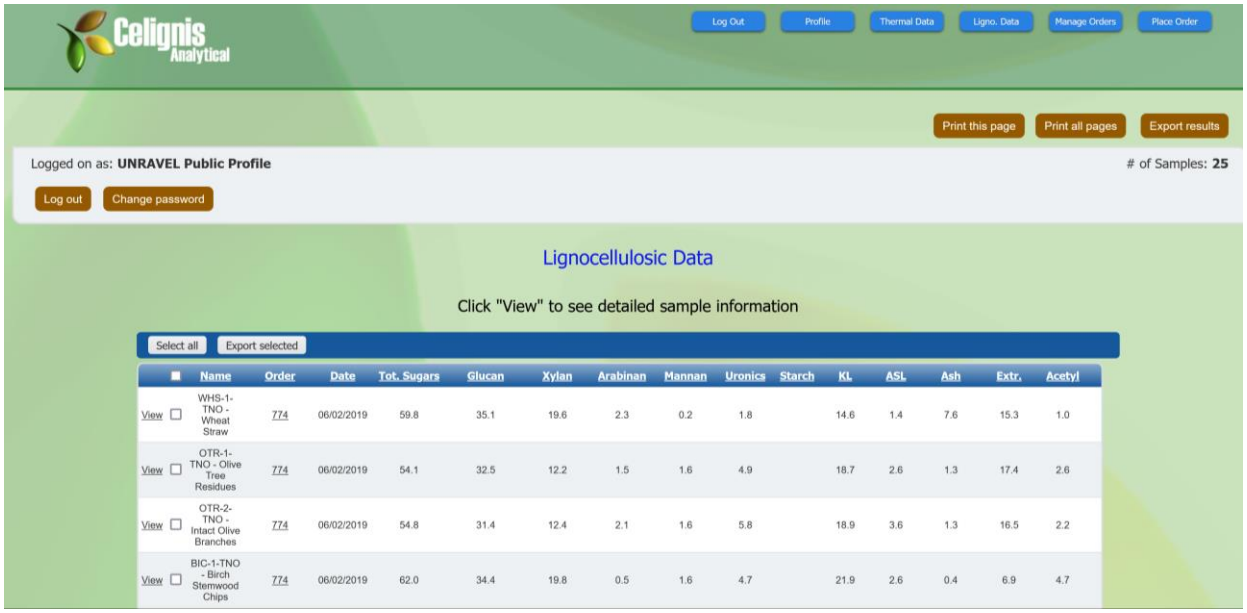
Data that has been assessed to be of particular importance for various knowledge communities include the compositional data generated during the analyses of different biomass samples which at the start of UNRAVEL had been considered suitable candidates for developing, testing and upscaling the biorefinery processes.

UNRAVEL partner Celignis, who has been responsible for analysing the UNRAVEL feedstock samples, provides the results in a public and openly accessible database (*Fig. 1*). The database can be accessed at www.celignis.com/output/analytical_customer_list.php?order=774 and via the UNRAVEL project website at http://unravel-bbi.eu/data-resources/.

In the future, such data will help scientists and the industry to make informed decisions about possible choices of feedstocks for specific applications of lignocellulosic biomass.

Other data that have been seen as relevant for wider stakeholder groups are the characterisation of agriculture and forestry residues and the lignin characterisation and dissolution properties together with the characteristics of lignin-based polyols for production of PUR insulation foams. The overview of current public data is given in Table 1.

Fig 1 The public database covering the composition of 25 UNRAVEL feedstock samples (screenshot)



		Name	Order	Date	Tot. Sugars	Glucan	Xylan	Arabinan	Mannan	Uronics	Starch	KL	ASL	Ash	Extr.	Acetyl
View	☐	WHS-1-TNO - Wheat Straw	774	06/02/2019	59.8	35.1	19.6	2.3	0.2	1.8		14.6	1.4	7.6	15.3	1.0
View	☐	OTR-1-TNO - Olive Tree Residues	774	06/02/2019	54.1	32.5	12.2	1.5	1.6	4.9		18.7	2.6	1.3	17.4	2.6
View	☐	OTR-2-TNO - Intact Olive Branches	774	06/02/2019	54.8	31.4	12.4	2.1	1.6	5.8		18.9	3.6	1.3	16.5	2.2
View	☐	BIC-1-TNO - Birch Stemwood Chips	774	06/02/2019	62.0	34.4	19.8	0.5	1.6	4.7		21.9	2.6	0.4	6.9	4.7

Table 1. Overview of fact sheets and target recipient groups

Fact Sheet	Key topics	Target groups
Fact Sheet #1 - Overall UNRAVEL Concept (see Annex A)	- The concept of a cascading lignocellulosic biorefinery - Biomass selection - The mild organosolv FABIOLA™ fractionation process - Pre-extraction for high quality lignin and extractives for side-valorisation - Overall sustainability of the UNRAVEL concept (LCA) - Pilot-scale results and steps towards market maturity	**BBI JU & Bio-based Consortium (incl. BIC Bioeconomy Platform)** **DG RTD** **EU Parliament** **DG CLIMA** **DG ENV** **DG AGRI** - DG Agriculture and Rural Development **EIT Climate KIC** **EEA** European Environment Agency **JRC EU Joint Research Centre**– EU Science Hub **JRC Smart Specialisation Platform 'Bio-Economy Pilot'** **European Committee of the Regions (CoR)** **EUBIA –** European Biomass Association **ITABIA** – Italian Biomass Association **DBFZ** – German Biomass Research Centre **EFI** - European Forestry Institute **ecoPlus** – Platform for Green Transformation & Bioeconomy (Austria) **EU EASME,** subgroup EU Eco-Innovation Multi-stakeholder Platforms on Sustainable Development Goals (SDG) **Circular bio-based Delta** - Alliance of Dutch provinces, businesses and knowledge centres in the delta region of the Netherlands **Biorizon** – Shared research center for technology development to produce aromatics derived from plant-based waste streams
Fact Sheet #2 - Sustainable Feedstock for Lignocellulosic Biorefinery	- Feedstock selection - Sustainability aspects - Competition over certain feedstock - Biomass allocation needs	
Fact Sheet #3 – High value products from high quality lignin	- The mild organosolv FABIOLA™ fractionation process - Pre-extraction for high quality lignin and extractives for side-valorisation - Performance of lignin-based polyols in PUR insulation foams against industry standards - Performance of lignin in bitumen roofing materials to replace the fossil-based SBS polymer	
Fact Sheet #4 – Valorising sugars from the hemicellulose fraction of lignocellulosic biomass	- The mild organosolv FABIOLA™ fractionation process - Enzymatic hydrolysis of cellulose pulp to produce glucose for fermentation - Fermentation process of glucose towards acetone as intermediate chemical or as make-up stream for solvent losses during Fabiola fractionation - Fermentation process of xylose towards xylonic acid as intermediate chemical - Perspective of sugar fermentation towards intermediate chemicals	

Fact Sheet #5 – Circularity aspects of a cascading lignocellulosic biorefinery	- The mild organosolv FABIOLA™ fractionation process - Use of fossil-based resources versus bio-based resources and the challenges to compete with the established oil refinery sector - Cascading approach to use biomass as long, often and efficiently as possible before energy recovery - Bio-based products are not automatically circular products	
Fact Sheet #6 – Processing of complex lignocellulosic biomass and mixed feedstocks (see Annex B)	- The concept of a cascading lignocellulosic biorefinery - The mild organosolv FABIOLA™ fractionation process - Pre-extraction prior to biomass fractionation results in reduced lignin content of pulps, increased hemicellulose sugar yield, improved lignin purity, reduced sugar degradation products and reduced acid dose requirements during fractionation - Successful fractionation of mixed biomass streams in the Fabiola™ process, allowing biorefinery operations to better deal with variations in (local) biomass supply and, hence, to reduce biomass transport costs	
Data	**Description of the data**	**Database/Repository**
Composition of 25 UNRAVEL feedstock samples	- Lignocellulosic profiles of biomass samples as reported in D2.2	http://unravel-bbi.eu/data-resources/
Lignin and lignin-based polyol characterization data	- Lignin dissolution data in several solvents - Molecular weight distribution of lignin samples and lignin fractions after solvent fractionation - Phenolic and aliphatic OH groups, glass transition temperatures and FTIR spectra of lignins - Properties of the lignin-based polyols after modification with ethylene carbonate	https://doi.org/10.1002/cssc.202001976
Characterisation data of agricultural and forestry residues	- Organic and inorganic elemental analysis of biomass samples - Lignocellulosic content - Extractives, uronic acids and acetyl content in biomass	https://doi.org/10.1016/j.indcrop.2021.113857

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ANNEX A: Fact Sheet #1 - Overall UNRAVEL Concept

UNRAVEL Project

FACTSHEET

UNRAVEL – A concept for a cascading, mild organosolv lignocellulosic biorefinery

Key findings from the UNRAVEL BBI JU research and innovation project (www.unravel-bbi.eu)

Why lignocellulosic biorefinery?

In 2016, the Paris Agreement entered into force as the legally binding international treaty on climate change. Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reduce global greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century.

One of the pillars of the European Union to reach treaty targets foresees more sustainable products and production processes that minimise the use of fossil resources. To achieve this, several policies and directives have been developed, among those the European Bioeconomy Strategy[1], the Renewable Energy Directive (RED III)[2], the EU Biorefinery Outlook to 2030[3] and Foresight Scenarios for the EU Bioeconomy in 2050[4]. A major challenge for the transition towards a low-carbon bio-based economy is the development of new value chains for innovative added-value products based on sustainable and industrially viable biomass.

Lignocellulosic biomass is an abundant and renewable resource from plants mainly composed of polysaccharides (cellulose and hemicelluloses) and an aromatic polymer (lignin) and represents an important category of feedstocks suitable for biorefinery processing. It has a high potential as an alternative to fossil resources to produce second-generation biofuels, bio-based chemicals and materials. Especially biomass residues that originate from forestry or agriculture could be sustainable feedstocks for higher value products that could help to avoid competition over hardwood with a generally high demand. Recent studies indicate that the feedstock availability in the EU is sufficient to meet the needs of the bio-based industry.

What is a lignocellulosic biorefinery?

The concept of biorefinery is the sustainable processing of biomass to obtain new bio-based products and/or bioenergy, often to reduce the need for fossil-based resources. Similar to the fossil-based refinery processes to isolate, convert and purify oil fractions for numerous applications, a biorefinery process isolates, converts and purifies fractions from biomass. However, biomass generally more heterogenous than oil and the industrial experience in processing is more limited.

Many biorefinery concepts start with a fractionation process to unravel the biomass into cellulose pulp, dissolved hemicellulose sugars and the precipitation of dissolved lignin. Depending on the fractionation technology applied, these fractions are more pure and/or better suitable for the downstream processing into new bio-based products. Currently, most technologies are optimised for a certain feedstock to be processed into a dedicated application. One of the novelties of the UNRAVEL project is that we found that the combination of biomass pre-extraction and fractionation enables the processing of complex

[1] https://op.europa.eu/en/publication-detail/-/publication/edace3e3-e189-11e8-b690-01aa75ed71a1/language-en/format-PDF/source-149755478
[2] https://ec.europa.eu/energy/topics/renewable-energy/directive-targets-and-rules_de
[3] https://op.europa.eu/en/publication-detail/-/publication/7223cd2e-bf5b-11eb-a925-01aa75ed71a1
[4] https://publications.jrc.ec.europa.eu/repository/handle/JRC123532

mixtures of feedstocks. The pre-extraction step acts as an upgrading of biomass (and the potential to valorise extractives) to obtain a homogeneous input of more pure lignocellulose, circumventing the disadvantages of having minerals or organic components that deteriorate the quality of the lignocellulosic fractions. Within UNRAVEL, several existing technologies for fractionation, conversion, modification and product applications have been integrated to obtain a new bio-based value chain. The new value chain uses a mix of hardwood wood chips, forest residues and bark, as well as straw and nutshell feedstocks via Fabiola™ processing to deliver extractives, lignin-based polyols for PUR/PIR foams, bitumen additives and chemical building blocks from the sugar fractions such as acetone or xylonic acid.

UNRAVEL – A novel concept for high value applications from lignocellulosic biomass

The novelty of the UNRAVEL project is the combination of a new biomass upgrading concept, an organosolv technology (Fabiola™) and a lignin precipitation technology (LigniSep) to obtain high purity cellulose, monomeric hemicellulose and a less-condensed lignin fraction that are suitable for downstream product applications.

The sugar fractions are fermented as this is a proven technology to obtain chemicals (acetone and xylonic acid were chosen as examples).
Lignin is applied both in PUR insulation foams and as a polymer replacement in bitumen roofing membranes.
The biomass extractives form a basis for further use and product development to optimise the full valorisation of residue streams.

The use of pre-extraction does also lead to a lower catalyst dosage during fractionation and improves the quality and quantity of sugars and lignin. The novel acetone-based fractionation technology improves the energy consumption of the biorefinery as well as the sugar yields and lignin quality.

The UNRAVEL concept at pilot scale

Upscaling of the lab-scale (20 liter) process to pilot-scale (460 liter) was performed at Fraunhofer CBP to validate the technology at TRL 5. After reference testing with beech wood, Industrial size birch wood chips (including bark and branches), wheat straw and a mixture of birch with bark and branches and wheat straw were fractionated after pre-extraction to remove minerals and (non-lignocellulosic) organic components.

Translation of the fractionation process to a pilot-scale showed similar performance as compared to the lab-scale processing with a good conversion of the polymeric hemicellulose sugars to mostly monomeric sugars and a relatively pure cellulose pulp. Continuous lignin precipitation by solvent evaporation using the LigniSep process was applied for the first time and resulted in high lignin yields that were easy to remove (did not stick to surface in the equipment) and with a good filterability. The fractionation performance and high product yield and purity of the cellulose pulp, the hemicellulose sugars and the lignin provides an excellent start position for improved process design at larger scale.

UNRAVEL lignin for the construction sector

The construction sector is one of the largest in the world and generally a material and energy intensive industry. Companies strive to lower their CO2 footprint to meet national and EU directives on climate change. One of the solutions that contributes to this target is the use of (partial) bio-based products and the inclusion of lignin is an interesting replacement for the conventional fossil-based ingredients. Within UNRAVEL, the use of (modified) lignin was tested in PUR insulation foams and in bitumen roofing membranes. Results for PUR foams indicated that the polyols prepared with Fabiola™ lignins were shown to have lower viscosity than polyols prepared from other technical lignins (Kraft and soda), indicating that potentially a higher amount of the Fabiola™ lignins can be used to replace the standard polyols. PUR foams with 20% substitution of the standard polyol were produced at pilot-scale and showed that the material meets the industrial specifications of PUR foams.

The use of lignin was also tested to replace a fossil-based polymer in bitumen. Results indicated that only 10% of the polymer could be replaced and that the behaviour of the product under cold temperature conditions limits further increase of lignin in the product. Overall, the use of lignin in construction products is a promising route to enhance the amount of bio-based products although specific challenges of lignin compatibility in certain applications is still a matter of further research.

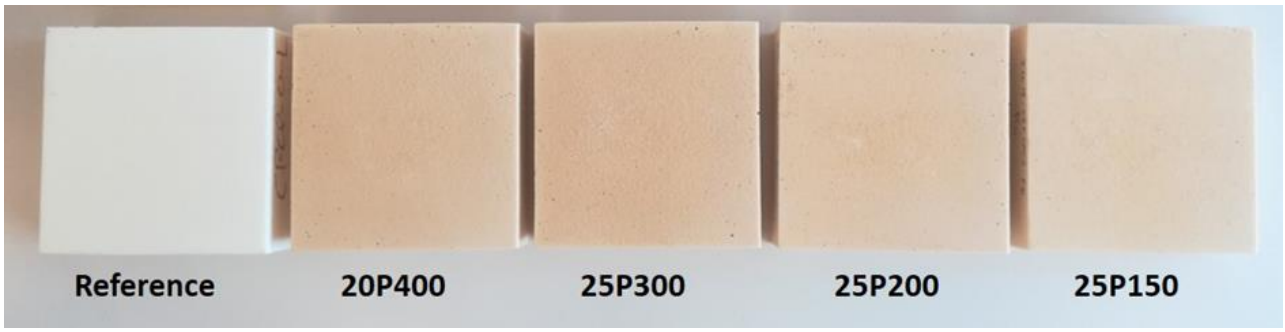

Figure: Pieces of large-scale foams (17 x 17 x 6 cm) prepared with 20% and 25% lignin-based polyols made from beech lignin and the reference with no lignin.

UNRAVEL breakthroughs on the way to novel and sustainable lignocellulosic value chains

➲ **Key achievement 1**

Successful upscaling of the complete UNRAVEL processes from laboratory to pilot-scale (TRL5).

➲ **Key achievement 2**

The pre-extraction strategy is broadly applicable to a range of (mixed) biomass inputs, allowing biorefinery operations to better deal with variations in (local) biomass supply and, hence, to reduce biomass transport costs.

➲ **Key achievement 3**

PUR insulation foams were produced by a novel process to obtain polyols using ethylene carbonate with up to 50% replacement of the standard polyol. Products meet industrial specifications.

➲ **Key achievement 4**

Successful fermentation of glucose and xylose towards acetone and xylonic acid as platform chemicals for the industry.

➲ **Key achievement 5**

The LigniSep continuous lignin precipitation technology was demonstrated at pilot scale and showed to substantially improve the lignin yields to over 95% compared to about 70% in conventional processes.

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Website All UNRAVEL Fact Sheets and other publications are available at:
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ANNEX B: Processing of complex lignocellulosic biomass and mixed feedstocks

UNRAVEL Project

FACTSHEET

Biorefinery for complex lignocellulosic biomass and mixed feedstocks

Key findings from the UNRAVEL BBI JU research and innovation project (www.unravel-bbi.eu)

Why lignocellulosic biorefinery?

In 2016, the Paris Agreement entered into force as the legally binding international treaty on climate change. Its goal is to limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reduce global greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century.

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A major challenge for the transition towards a low-carbon bio-based economy is the development of new value chains for innovative added-value products based on sustainable and industrially viable biomass. Lignocellulosic biomass is an abundant and renewable resource from plants mainly composed of polysaccharides (cellulose and hemicelluloses) and an aromatic polymer (lignin) and represents an important category of feedstocks suitable for biorefinery processing. It has a high potential as an alternative to fossil resources to produce second-generation biofuels, bio-based chemicals and materials. Especially biomass residues that originate from forestry or agriculture could be sustainable feedstocks for higher value products that could help to avoid competition over hardwood with a generally high demand. Recent studies indicate that the feedstock availability in the EU is sufficient to meet the needs of the bio-based industry.

What is a lignocellulosic biorefinery?

The concept of biorefinery is the sustainable processing of biomass to obtain new bio-based products and/or bioenergy, often to reduce the need for fossil-based resources. Similar to the fossil-based refinery processes to isolate, convert and purify oil fractions for numerous applications, a biorefinery process isolates, converts and purifies fractions from biomass. However, biomass generally more heterogenous than oil and the industrial experience in processing is more limited.

Many biorefinery concepts start with a fractionation process to unravel the biomass into cellulose pulp, dissolved hemicellulose sugars and the precipitation of dissolved lignin. Depending on the fractionation technology applied, these fractions are more pure and/or better suitable for the downstream processing into new bio-based products. Currently, most technologies are optimised for a certain feedstock to be processed into a dedicated application.

[1] https://op.europa.eu/en/publication-detail/-/publication/edace3e3-e189-11e8-b690-01aa75ed71a1/language-en/format-PDF/source-149755478
[2] https://ec.europa.eu/energy/topics/renewable-energy/directive-targets-and-rules_de
[3] https://op.europa.eu/en/publication-detail/-/publication/7223cd2e-bf5b-11eb-a925-01aa75ed71a1
[4] https://publications.jrc.ec.europa.eu/repository/handle/JRC123532

One of the novelties of the UNRAVEL project is that we found that the combination of biomass pre-extraction and fractionation enables the processing of complex mixtures of feedstocks. The pre-extraction step acts as an upgrading of biomass (and the potential to valorise extractives) to obtain a homogeneous input of more pure lignocellulose, circumventing the disadvantages of having minerals or organic components that deteriorate the quality of the lignocellulosic fractions. Within UNRAVEL, several existing technologies for fractionation, conversion, modification and product applications have been integrated to obtain a new bio-based value chain. The new value chain uses a mix of hardwood wood chips, forest residues and bark, as well as straw and nutshell feedstocks via Fabiola™ processing to deliver extractives, lignin-based polyols for PUR/PIR foams, bitumen additives and chemical building blocks from the sugar fractions such as acetone or xylonic acid.

The UNRAVEL approach on processing complex lignocellulosic biomass

UNRAVEL feedstocks have been selected based on their significant availability in the EU with also a focus on varying lignocellulosic composition and amount of extractives in the biomass. In addition, a variety of different feedstock categories was included in the selection. Moreover, we target the processing of mixed complex lignocellulosic feedstocks. Examples of feedstocks used in UNRAVEL are: agricultural residues (wheat straw, corn stover), forestry residues (birch with bark and branches), municipal solid waste (road-side grass) and food-processing residues (almond shells). The latter category is especially challenging because these residues are relatively small and heterogeneous. In addition, the lignocellulose content can be too low whereas the stalks contain more lignocellulose but these are considered agricultural residues. .

The successful processing of complex lignocellulosic biomass can be substantially hampered by the presence of non-lignocellulose components, such as minerals and organic extractives. Minerals can be problematic as they lower the yields for downstream valorisation by enhancing the sugar degradation during fractionation. Organic extractives have a negative effect on the purity of the lignin and limit its reactivity, which can affect product applications. Therefore, complex feedstocks are first pre-extracted under mild conditions using aqueous acetone and temperatures between 50 and 75 C. After removing the extractives, the biomass is fractionated using the Fabiola™ process. In this mild organosolv process the target compounds cellulose, hemicellulose and lignin are obtained. To make the biorefinery process more efficient and economically and environmentally more sustainable, UNRAVEL also strives to valorise the above mentioned extractives. Possible applications can be found in the health, pharma, green chemistry and food sectors.

Results show that pre-extraction prior to fractionation generally improves the overall biorefining performance, specifically by producing more pure pulps with a reduced lignin content (higher quality), increasing the hemicellulose sugar yield and improving lignin purity, and by implication, improve the lignin yield as less of it ends up in the pulp. In addition, lower amounts of toxic sugar degradation products were found. This facilitates the valorisation of the hemicellulose sugars for example by fermenting them to xylonic acid or other platform chemicals. Pre-extraction also significantly reduces the acid

amounts that are required during the fractionation process, especially for herbaceous feedstocks. This makes the fractionation process less costly, more environmentally benign and less hazardous. We further expect that lower sulphate concentrations that result from reduced acid doses, combined with the removal of chloride from pre-extraction will lead to less corrosion of the process equipment. This will lower the processing costs further and make biorefinery more efficient.

- ✓ A pre-extraction step improves the overall performance of lignocellulose biorefining
- ✓ Yield and purity of target compounds sugars and lignin are improved
- ✓ Lower acid doses are required which makes the fractionation process less costly, more environmentally benign and less hazardous

UNRAVEL processing of mixed lignocellulosic biomass

Targeting novel products based on sustainable feedstock requires an integrated view of the whole biomass-to-product chain, from feedstock supply chains to biorefinery processing and product development. An important aspect of a sustainable and economically viable biorefining process is the use of a wide variety of lignocellulosic feedstocks. Large scale biorefineries must have the flexibility to process multiple or mixed feedstocks to cope with biomass compositions and availabilities that can vary seasonally and geographically. Furthermore, negative impacts on the environment and the society that could result from a high demand of one single biomass should be prevented as far as possible. This can be achieved by minimising the competition with other environmentally friendly uses of the same kind of biomass or by preventing unintended incentives to extract unsustainable amounts of biomass from agriculture and/or forestry.

To contribute to a higher biomass flexibility of biorefineries, UNRAVEL processed a mixture of wheat straw and birch with bark and branches as one example of feedstocks with very different properties. For the mixed feedstocks we combined the pre-extraction and Fabiola™ fractionation steps. The obtained cellulose, hemicellulose and lignin were characterised and successfully tested in the UNRAVEL target products (i.e. acetone, xylonic acid, PUR foams and bitumen roofing membranes). These results demonstrate the robustness of the Fabiola™ process and indicate that processing of mixed feedstocks is possible in future biorefinery operations at industrial scales.

- ✓ The processing of mixed feedstocks allows biorefinery operations to better deal with variations in local biomass supply
- ✓ Working with mixed feedstocks can help to reduce feedstock cost
- ✓ Demonstrated feedstock flexibility can avoid competition over hardwood as feedstock with generally high demand for other uses.

UNRAVEL breakthroughs on the way to flexible and sustainable biorefinery with mixed and complex feedstocks

- **Key achievement 1**
  Successful **upscaling of the complete UNRAVEL processes** from laboratory to pilot-scale (TRL5) using complex lignocellulosic feedstocks and a mixture of feedstocks.

- **Key achievement 2**
  The **pre-extraction strategy** is broadly applicable to a range of (mixed) biomass inputs, resulting in reduced lignin content of pulps, increased hemicellulose sugar yield, improved lignin purity, reduced sugar degradation products and reduced acid dose requirements during fractionation.

- **Key achievement 3**
  Successful **fractionation of mixed biomass** streams in the Fabiola™ process, allowing biorefinery operations to better deal with variations in (local) biomass supply and, hence, to reduce biomass transport costs.

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