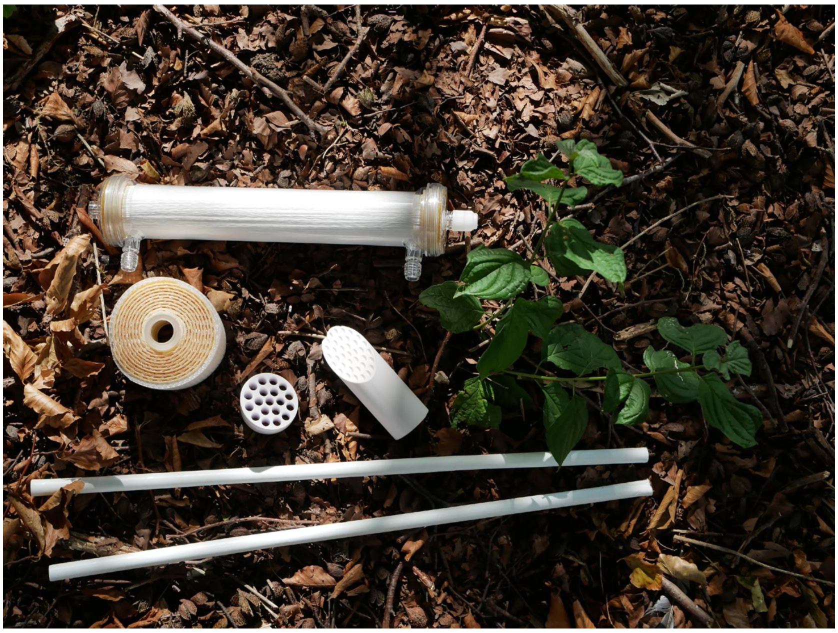

TASK XVII:

MEMBRANE PROCESSES IN BIOREFINERIES

Final Report

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EXCECUTIVE SUMMARY

The transition from a society largely dependent on fossil-based materials to a climate-smart society based on biomass does not only mean a change in the raw material base but will also require other separation processes and concepts than used during the "oil era". In current petro-chemical refineries distillation is the unit operation that dominates the separation concepts as most compounds are volatile. In contrast to petro-chemical compounds, most compounds derived from biomass are non-volatile. Therefore, molecular size, charge and solubility are the main separation characteristics of extracted biomass compounds, which make membrane processes a natural key separation technique in biorefineries.

The goal of the extensions IETS Task XVII on “Membrane processes in biorefineries” was to build upon the initial phase of the Task by extending the learnings from the lignocellulosic biorefineries other types of biorefineries plus extending to additional subtasks.

To achieve this a group of 25 academic and industrial partners from 8 IETS countries was formed working on six subtasks covering separations in biorefineries (Subtask A), integration and optimization of membrane processes in biorefineries (Subtask B), fouling and cleaning of membranes in biorefineries (Subtask C), pre-treatment of biomass process streams before membrane separation (Subtask D), emerging membrane processes (Subtask E) and water and wastewater treatment in biorefineries (subtask F).

The results for the different projects associated to the Task were shared with participants in online workshops and Task meetings. During the Task meeting at Euromembrane 2021 in Copenhagen, several areas for further work of the Task have been identified, in particular membrane bioreactor for continuous production of biofuels and biochemical using fermentation processes related to subtask B and pervaporation, forward osmosis and vapor permeation related to subtask E.

Overall, the Task managed to develop the industrial and academic network further and achieved an excellent level of co-operation and dissemination which will support reducing of energy in biorefineries by the integrate and optimization of membrane processes.

1. CONSORTIUM

The consortium of Task XVII on “Membrane processes in biorefineries” consisted of 25 academic and industrial partners from 8 IETS countries. In Table 1, an overview of the consortium partners is given.

Table 1: Academic and industrial partners of Task XVII on “Membrane processes in biorefineries”.

Denmark • Alfa Laval • Aquaporin • Kaffe Bueno • LiqTech International • Nordic Sugar • Novozymes • Aalborg University • Technical University of Denmark (DTU) • University of Southern Denmark (SDU) **France** • CNRS University of Toulouse • Institut Europeen des Membranes **Italy** • CNR – Institute on Membrane Technology **Portugal** • Instituto Superior Técnico • Universidade NOVA de Lisboa	**The Netherlands** • Pentair • TNO • University of Twente **Sweden** • Ecohelix • RISE • Chalmers University of Technology • Lund University • Umeå University **Germany** • University of Applied Sciences Mittelhessen • Fraunhofer Institute **Austria** • AEE – Intec

2. BACKGROUND

The Task XVII – previously Annex XVII - originally started in 2014 under the title “Membrane processes for energy-efficient separation of lignocellulosic biomass components” coordinated by Prof. Ann-Sofi Jönsson from the Department of Chemical Engineering at Lund University, Sweden. In this phase the initial co-operation platform for the Task XVII was established. During the final dissemination phase of the first period of the Task from 2014 – 2017, it was concluded that some subtasks such pre-treatment and fouling/cleaning require further investigations, while other areas such as emerging membrane processes and water and wastewater treatment in biorefineries would be important to investigate. Furthermore, it was recommended to extend the Task XVII beyond lignocellulosic biorefineries. Based on this a second phase of the Task XVII under the title “Membrane processes in biorefineries” was started in 2019 until 2022 under the management of Prof. Frank Lipnizki from the Department of Chemical Engineering at Lund University, Sweden. During this period, the initial network of industrial and academic researchers was significantly extended, and new countries were included. The goal of the Task XVII was to maintain, develop and lead an international network supporting the research and development of energy-efficient membrane processes in biorefineries. Thus, to support biorefineries to optimize their energy-efficiency by integrating membrane processes for energy demanding fractionation and separation processes.

3. IMPLEMENTATION

The IETS Task XVII “Membrane processes in biorefineries” supported the research and development of sustainable and energy-efficient membrane separation processes using renewable resources in the concept biorefineries with the goal to produce simultaneously, biochemical, biofuels, heat and electricity. Thus, Task XVII contributed to the overall goal of IETS to optimize industrial energy-related technologies and systems by:

- Maintaining and extending a network of international industrial and academic researchers with the fields of membrane processes and biorefineries.
- Consolidate and disseminate information on the latest research and trends on membrane processes in biorefineries. This was achieved through regular Task meetings and workshops plus contributions to ExCo meeting of the IETS and its webpage.
- Research on fouling and cleaning in lignocellulosic biorefineries using novel in-situ monitoring techniques.
- Consolidating the state of the art on integration and optimization of membrane processes in biorefineries.
- Mapping and development of guidelines for the integrate of emerging membrane processes for biorefineries.

The work in Task XVII was structure in the following 6 Subtasks:

- Subtask A: Separation in biorefineries
- Subtask B: Integration and optimization of membrane processes in biorefineries
- Subtask C: Fouling and cleaning of membranes in biorefineries
- Subtask D: Pretreatment of biomass process streams before membrane separation
- Subtask E: Emerging membrane processes
- Subtask F: Water and wastewater treatment in biorefineries

The outcome of the different subtasks are described in the result section.

4. RESULTS

The work in Task XVII resulted in an extended network of 25 high profile industrial and academic partners from 8 IETS countries. In the Task the partners exchanged information on their individual and common research projects and discussed general research results and trends. The results from the projects but also the Task work itself was disseminated through presentations at conferences as well as peer-revied scientific and common scientific articles. The Task had not only regular Task meetings and Task workshops but also Subtask and co-ordination meetings with other Tasks. The project started with a kick-off meeting in combination with the “Engineering with Membranes” conference in Båstad Sweden on 8th of April 2019. The last Task meeting so far was at “Euromembrane” conference in Copenhagen, Denmark, on the 30th of November.

The results highlighted in this section are mainly obtained by the individual research groups. This owes to the fact that the individual project partners had been successful in obtaining individual funding, but no joint project was received. However, the results were presented and discussed at the Task workshops and Subtask meetings.

In the following the results for the individual subtasks will be presented.

4.1 Subtask A: Separation in biorefineries

This subtask combined and extended the Subtask A (Recovery of biomass components) and Task B (Sustainable and energy-efficient separation methods in biorefineries) from the original Task (Annex) XVII and was headed by Knud Villy Christensen, University of Southern Denmark (SDU), Denmark. The subtask addressed the following challenges:

- Mapping of separation challenges in biorefineries.
- Benchmarking of separation technologies for separation duties.
- Selection tool for separation processes in biorefineries.

In this subtask several projects were started focusing on membrane processes in upstream and downstream separations. In relation to the subtask two key projects were started (1) Græs4Food and (2) Farm2Furan.

Græs4Food project

This project was headed by Aalborg University (Denmark) to develop a new process including membrane technology for refining high-quality food protein from clover grass and alfalfa. On the background that the demand for sustainable plant-based proteins for food is increasing, there is a huge potential in extracting such proteins from green biomasses. The project is based on previous laboratory-scale work using membrane filtration to extract the food protein. It is planned that the experiences from this project will be used to optimize and scale up the process on a pilot scale with the goal of transferring this process to a large plant production plant and other grass plant proteins.

Farm2Furan project

In the Farm2Furan project at Lund University (Sweden) focus is on developing a value chain for chemicals production as part of a future biorefinery based on surplus agricultural biomass streams in Sweden, i.e. wheat bran and – straw, oat hulls, beet sugar and -molasses. Target products are 5-hydroxymethylfurfural (HMF) as a versatile platform chemical for chemical- and fuel industries, and some of its derivatives for use as building blocks for plastics and –surface coating applications. The use of membrane technology was in particular investigated with regard to use of molasses, a sugar mill by-product with low value that today is used primarily for animal feed. However, molasses contains large amounts of sucrose which, if purified, could be used for other purposes. In the initial study [1], purification by membrane filtration using ceramic tubular ultrafiltration (UF) and nanofiltration (NF) was evaluated. NF purifies sucrose by removing small compounds, while UF removes larger compounds. Based on the results, high fluxes could be obtained, and it was possible to clean the membranes sufficiently after processing. Sucrose was separated from other compounds, but the separation efficiency was generally higher with diluted molasses compared with concentrated molasses. This could be explained by more severe fouling when filtering dilute molasses or potentially due to aggregate formations in the molasses as our analysis showed. However, this initial study showed the potential of ceramic UF and NF membranes for sucrose purification from molasses. In the subsequent study [2], the pre-treatment of crude molasses through purification using membrane filtration was investigated with focus on 5-hydroxymethylfurfural production. The pre-treatment processes – ultrafiltration and nanofiltration - were evaluated with respect to the sucrose hydrolysis reaction rates and for the downstream 5-hydroxymethylfurfural production. Results from the ultra- and nanofiltration experiments showed good fluxes and high flux recovery after cleaning and the ability to purify sucrose. The sucrose hydrolysis results showed an improved reaction rate for molasses (concentrate) processes with nanofiltration, while the ultrafiltration permeate showed no major difference from the crude molasses, indicating that the inhibitory compounds are of low molecular weight. However, the ultrafiltered molasses showed highly efficient fructose conversion and 5-hydroxymethylfurfural selectivity in the biphasic acid-catalysed dehydration, compared to fructose conversion of the crude molasses.

Overall, these projects highlighted the potential of membrane technology as key separation processes in the concept of biorefineries using different types of feedstocks.

The following publications related to Subtask A were prepared in the duration of the Task:

[1] M. Sjölin, M. Sayed, J. Thuvander, F. Lipnizki, R. Hatti-Kaul, O. Wallberg: Effect of membrane purification and concentration of sucrose in sugar beet molasses for the production of 5-Hydroxymethylfurfural, Chemical Engineering Research and Design, https://doi.org/10.1016/j.cherd.2022.01.007.

[2] M. Sjölin, J. Thuvander, O. Wallberg and F. Lipnizki: Purification of sucrose in sugar beet molasses by utilizing ceramic nanofiltration and ultrafiltration membranes. Membranes, 2020, 10, 5. doi.org/10.3390/membranes10010005.

4.2 Subtask B: Integration and optimization of membrane processes in biorefineries

This subtask continues and extends the Subtask C (Design and optimization of membrane processes in biorefineries) from the original Task (Annex) XVII and was led by Lidietta Giorno, National Research Council of Italy - Institute on Membrane Technology (ITM-CNR), Italy. The subtask had the following aims:

- Optimization of membrane processes to reduce investment and operating costs.
- Adjusting operating parameters to minimise energy consumption.
- Techno-economical evaluation of hybrid processes in biorefineries.

To achieve this a mapping of the state-of-the art is currently on-going headed by ITM-CNR (Italy). Furthermore, work at a Lund University (Sweden) and the University of Applied Sciences Mittelhessen (Germany) focused on the integration and optimization of membrane processes in the concept of lignocellulosic biorefineries. The work can be divided into three key areas based on the pulping process used: sulfite, kraft or thermomechanical pulping.

Sulpfite pulping process

The separation and purification of galactoglucomannan from sodium-based spent sulfite liquor was a research focus in project at Lund University (Sweden) [3]. On-site pilot studies of this application with a plate-and-frame module using polymeric UF membranes showed that high and stable average fluxes can be achieved over several concentration cycles. However, in all of these cases, the lignin and galactolgucomannan had a molecular weight of the same size meaning other methods were needed for the actual separation of these components. Therefore, antisolvent precipitation [4] and adsorption [5] were used for the separation of these components. The results from these studies showed that the use of membrane filtration prior to the antisolvent precipitation was beneficial because lower amounts of antisolvent was thus required for the process, which in turn would decrease the operational cost. In regard to the adsorption, the membrane filtration was beneficial as a post-treatment step due to the concentrations being lower in the in-going spent sulfite liquor, which in turn results in a smaller adsorption column, lower regeneration frequency and lower regenerant demand [6]. In another study [7] related to spent sulfite liquor by the University of Applied Sciences Mittelhessen (Germany) ceramic hollow-fiber membranes were tested as an alternative to common membrane technologies for the concentration of spent sulfite liquor. Three ceramic hollow-fiber membranes (3, 8, and 30 nm) in different membrane processes (fed-batch and total recycle mode) were evaluated and compared the widely used tubular membrane geometry. Furthermore, backflushing as a strategy to reduce membrane fouling during filtration was tested. Comparing the two membrane geometries revealed that wall shear stress was the most important process parameter for the assessment of membrane performance according to permeate flux. A higher wall shear stress resulted in a higher permeate flux. Due to the smaller inner diameter of the hollow-fiber membranes, higher wall shear stress was achieved more easily. It was further found that backflushing had no effect on the permeate flux during the concentration experiments.

Kraft pulping process

A study at the Lund University (Sweden) related to the Kraft process focused on the separation of low-molecular-weight lignin from the ultrafiltration permeate of high-molecular-weight lignin concentration [9]. In this work, nanofiltration was evaluated for the separation and concentration of low-molecular-weight lignin from the ultrafiltration permeate. It was shown that the nanofiltration process is able to produce a concentrated lignin fraction, which can be either used to produce valuable chemicals or used to make lignin oil.

Thermomechanical pulping process

The recovery of hemicelluloses from the process water of a thermomechanical pulp mill processing spruce was investigated at Lund University (Sweden). The work was carried out on pilot scale study [9] using a MF-UF membrane cascade process. The results showed that the limiting part of the process was the MF stage. This was due to the high risk of fouling of the ceramic MF membranes used for the colloidal extractives removal, while the UF stage was operated at stable fluxes and high volume reductions. Further improvements in the process of removing the colloidal extractives can have a great impact on the overall process economy.

Related to Subtask B a general overview of the application potential of membrane processes in the concept of lignocellulose biorefineries was also prepared by Lund University (Sweden) [10]. The potential of the membrane processes in this conversion of pulp mills into lignocellulosic biorefineries was highlighted in three applications related to kraft/sulphate, sulphite and thermomechanical pulping. Furthermore, the challenges of membrane fouling and cleaning with regard to pulping industry was discussed and an outlook on future developments of membranes in biorefineries was given.

Finally, a project on the continuous processing of biofuel and biochemical production using membrane processes is ongoing at Lund University (Sweden) [11]. In this project the production of butanol from hydrolysates of lignocellulosic biomass will be investigated. The goal is to use a membrane bioreactor concept – a standard concept for wastewater treatment industry - to move towards a continuous concept with higher yield. Further, energy-efficient butanol pre-concentration by water-exchange with forward osmosis will be studied.

The projects related to this subtask demonstrated how membrane processes can be successfully integrated in different pulping processes on lab and partly pilot scale.

The following publications related to Subtask B were prepared in the duration of the Task:

[3] B. Al-Rudainy, M. Galbe, O. Wallberg: Influence of prefiltration on membrane performance during isolation of lignin-carbohydrate complexes from spent sulfite liquor. Separation and Purification Technology, 2017, 187, 380-388. DOI: 10.1016/j.seppur.2017.06.031.

[4] B. Al-Rudainy, M. Galbe, H. Schagerlöf, O. Wallberg: Antisolvent precipitation of hemicelluloses, lignosulfonates and their complexes from ultrafiltrated spent sulfite liquor (SSL), Holzforschung 2018, 72(10), 839-850. DOI:10.1515/hf-2017-0218

[5] B. Al-Rudainy, M. Galbe, O. Wallberg: Hemicellulose Recovery from Spent-Sulfite-Liquor: Lignin Removal by Adsorption to Resins for Improvement of the Ultrafiltration Process, Molecules 2020, 25(15), 3435. DOI: 10.3390/molecules25153435

[6] B. Al-Rudainy, M. Galbe, F. Lipnizki and O. Wallberg. Galactoglucomannan recovery with hydrophilic and hydrophobic membranes: Process performance and cost estimations. Membranes, 2019, 10:9(8):99. doi.org/10.3390/membranes9080099

[7] D. Humpert, M. Ebrahimi, A. Stroh and P. Czermak Recovery of lignosulfonates from spent sulfite liquor using ceramic hollow-fiber membranes. Membranes, 2019, 9, 45; doi:10.3390/membranes9040045.

[8] M. Battestini Vives, J. Thuvander, A. Arkell and F. Lipnizki: Low-molecular-weight lignin recovery with nanofiltration in the kraft pulping process. Membranes, 2022, 12, 310. https://doi.org/10.3390/membranes12030310.

[9] J. Thuvander, F. Lipnizki and A.-S. Jönsson: On-site recovery of hemicelluloses from thermomechanical pulp mill process water by microfiltration and ultrafiltration. Journal of Wood Chemistry and Technology, 39, 2019, doi: 10.1080/02773813.2019.1565865.

[10] F. Lipnizki, G. Rudolph, J. Thuvander, B. Al-Rudainy and M. Battestini Vives: Anwendungspotential von Membranprozessen im Konzept der Lignocellulose-Bioraffinerien (Application potential of membrane processes in the concept of lignocellulose biorefineries). Chemie Ingenieur Technik, 93 (2021), http://doi.org/10.1002/cite.202100018.

[11] Energy-efficient valorization of diluted biopolymers from residual waste), Project No. 49511-1, funded by Energimyndigheten, 2020 – 2022.

4.3 Subtask C: Fouling and cleaning of membranes in biorefineries

This subtask continues and extends the Subtask D (Fouling and cleaning of membranes in biorefineries) from the original Task (Annex) XVII and was headed by Maria Noberta de Pinho, IST, Portugal with the following focus areas:

- In-situ analysis of fouling and cleaning.
- Modelling and fouling prediction.
- Techno-economical optimisation of fouling and cleaning.

The work in this subtask can be divided into two areas: (1) techniques to investigate membrane fouling and cleaning and (2) development of low fouling membranes.

Techniques to investigate membrane fouling and cleaning

In this area a comprehensive overview of in situ real-time monitoring techniques for membrane fouling in the biotechnology, biorefinery and food sectors was compiled by Lund University (Sweden) [12].

Membrane fouling and cleaning was studied on tubular polymeric UF membranes that have been in operation for several months for concentrating bleach plant effluent from a sulphite pulping process at Lund University (Sweden) [13]. The membrane fouling layer was investigated with scanning electron microscopy together with energy dispersive spectroscopy (SEM-EDS), and attenuate total reflection Fourier transformed infrared spectroscopy (ATR-FTIR). In additional, the fouling layer was acid hydrolysed with sulfuric acid and the hydrolysate subsequently analysed with high-performance anion-exchange chromatography coupled with pulsed amperometric detection (HPAEC-PAD), and foulants were extracted from the membrane with a mixture of acetone and deionized water using a Soxhlet extractor and subsequently analysed with heteronuclear single quantum coherence 2D nuclear magnetic resonance spectroscopy (HSQC-2D-NMR). The comprehensive analyses revealed that at the end of the lifetime, a roughly 4.5 µm thick fouling layer had established itself on the membrane. The fouling layer consisted mostly of compounds containing magnesium. The atomic weight percentage of the magnesium was the highest 2 µm below the fouling layer surface; it rapidly declined towards the membrane surface. Further into the membrane, silicon was detected with a maximum content of 10 % in atomic weight, 10 µm away from the membrane surface. In the membrane, the magnesium content was marginal. With regard to the composition of the bleach plant effluent and the operation conditions in the plant, it is likely that the magnesium originated from precipitation of magnesium hydroxide $Mg(OH)_2$. Furthermore, monosaccharides were detected in the hydrolysate of the fouled membranes but only glucan existed in quantifiable amounts. The analysis of the acetone-water extract with HSQC-2D-NMR could neither support nor disprove the presence of saccharides in the fouling layer. Indications for the existence of fatty acids and resin acids in the fouling layer were found, but it was not possible to exclude the other notorious foulant, lignin, as reason for the detected membrane fouling. The ATR-FTIR analysis did not result in reasonable results. Probably, the fouling layer was too thick and too rough and therefore proper contact with the ATR crystal was not possible. Even the use of deuterium oxide to support the contact between the membrane and the crystal did not help to improve the measurements. Interestingly, brown spots, visible with the human eye, were found in the non-woven support layer on the back side of the membrane. According to SEM-EDS analysis, they consisted mainly of magnesium. So far it was not possible to resolve the reason for these spots on this side of the membrane. Membrane cleaning was investigated with an alkaline cleaning agent on samples from the fouled membrane. The samples were dipped in the cleaning agent for 1 h and 20 h and were afterwards analysed. After 1 hour cleaning, results from SEM-EDS showed a visual fouling layer on the membrane surface consisting mainly of magnesium. However, no visible difference could be made out between the SEM image of a 20 h cleaned sample and a pristine membrane sample. EDS detected only traces of magnesium on the 20 h cleaned sample. Similar to the fouled sample, analysis with ATR-FTIR was not possible for the 1 h cleaned membrane, but generated reasonable spectra for the 20 h cleaned sample. Results from this analysis support the theory of magnesium hydroxide precipitation on the membrane, as the stretching vibration in the crystal structure of $Mg(OH)_2$, and a Mg-O stretching vibration was detected. Acid hydrolysis of the cleaned membranes revealed that 30 % of the amount of saccharides was removed after 1 h of cleaning and 40 % of the amount saccharides was removed after 20 h of cleaning.

Membrane fouling and cleaning was investigated on a polymeric UF membrane fouled with thermomechanical pulping process water in various lab-scale set-ups under various operation conditions at Lund University (Sweden). Fouled and cleaned membranes were among others analyzed with scaing electron microscope. (SEM) [14], ATR-FTIR, Brunauer-Emmert-Teller nitrogen adsorption desorption analysis (BET) [15] and Quartz crystal microbalance with dissipation monitoring (QCM-D) [13]. The studies revealed that membrane fouling from UF of the process water results in the formation of a gel layer formation, but also pore blocking and pore narrowing was observed. The analyses found that mainly polysaccharides in the form of hemicelloses and especially galactoglucomannan adsorbed on the membrane and formed the gel layer. Hereby, galactoglucomannans adsorbed immediately as a thin rigid layer. The adsorption continued thereafter but at a much slower speed. Hydrophobic wood extractives have additionally been detected in the fouling layer [14, 16, 17]. The extractives in the process water create colloidal droplets that are sterically and electrostatically stabilized by galactoglucomannans on the outside. It is likely that these colloids getting slowly embedded in the gel layer with time. Furthermore, dissolved wood extractives could also enter the membrane pores and could be the reason for the observed pore blocking and pore narrowing. Precipitation of inorganic compounds was not found in this process.

Membrane cleaning was performed with an alkaline cleaning agent and a home-made enzymatic cleaning cocktail with six commercially available enzyme classes β-glucanase, cellulase, mannanase, xylanase, lipase, and cutinase as alternative cleaning agent [14]. In the lab-scale experiment, it was found that alkaline cleaning could recover the membrane capacity completely after one fouling phase and enzymatic cleaning was not successful in recovering the membrane capacity after one fouling phase. However, this cleaning agent showed promising results in combination with subsequent alkaline cleaning. In an experimental series, the same membrane was fouled and cleaned several times, alkaline cleaning was not anymore able to recover the membrane capacity. Cleaning after the second fouling phase resulted in a dramatically declined capacity. Therefore, after the third fouling phase, the membrane was cleaned with the enzymatic cocktail instead of the alkaline agent. Here, enzymatic cleaning helped to not only recover the capacity completely in comparison to the capacity before the third fouling but improved it even further. Hence, it can be concluded that occasional enzymatic cleaning can boost the membrane process and could thus prolong the membrane lifetime.

Another alternative method used to study membrane fouling was fluid dynamic gauging (FDG) [18]. In a study by Chalmers University (Sweden), fluid dynamic gauging was used to investigate the cohesive strength of the membrane fouling layer formed during cross-flow microfiltration of microcrystalline cellulose. Fouling behavior was compared at two pH levels (i.e. different surface charges of the particles and membranes) with two membranes (i.e. regenerated cellulose and polyethersulphone). It was found that a suspension at low pH, where the surface charge of the particles is close to zero, resulted in thicker and stronger surface fouling layers (668 ± 66 µm thick at a shear stress of 36 Pa for the regenerated cellulose membrane). The permeate flux was reduced by 62% during the first 1000 s. For close-to-neutral pH, where the particles are negatively charged, the fouling layers were thinner and less resistant to shear stress (290 ± 77 µm thick at a shear stress of 36 Pa) and the decline of the flux was faster: a 90% decrease was recorded during the initial 1000 s. The differences in flux decline behaviour suggest a more pronounced blocking of the pore openings for the membranes at the higher pH. Similar fouling behavior was observed for the two membranes. An atomic force microscope equipped with a colloid probe was used to evaluate particle/particle and particle/membrane interactions.

In an extension of previous study by Chalmers University (Sweden) [18] crossflow microfiltration of a wood material, namely microcrystalline cellulose (MCC) with particles bigger than 5.4 µm and smaller than 56.4 µm, to study in situ the cohesive strength of the membrane surface fouling formed under different crossflow regimes. Using regenerated cellulose membrane with a nominal pore size of 0.2 µm, filtration experiments with FDG measurement show that the crossflow regime can lead to the formation of surface fouling layers with distinct cohesive strength. Fouling formed in turbulent/transitional crossflow was stronger and its removal required more liquid shear stress compared to the layers formed in laminar crossflow. The fouling layers that can withstand the minimum shear of 35 Pa from the FDG sensor with turbulent/transitional crossflow were, on average 294 ± 10 µm thick, in contrast to those formed in laminar crossflow, which were significantly thinner (144 ± 73 µm at 35 Pa shear stress, $p < 0.05$). On the other hand, turbulent/transitional crossflow reduced material deposition significantly ($p < 0.05$). After 1000 s filtration, 0.117 ± 0.003 kg m−2 MCC were found on the turbulent/transitional crossflow membranes, compared to 0.134 ± 0.005 kg m−2 in the laminar crossflow situation. Moreover, a similar permeate flux was observed in all experiments. This work highlights the necessity of developing membrane cleaning protocols based on the fouling layer properties, rather than on the permeate flux decline.

Development of low fouling membranes

One approach to reduce the impact of fouling is the development of low fouling membranes. Different approaches to produce low fouling membranes were investigated by Lund University (Sweden).

A novel approach for membrane modification to improve separation performance and antifouling stability was proposed [20]. It was found that the addition of Praestol 859 into the coagulation bath suppressed the macrovoid formation in the membranes supporting layer due to the decrease of “solvent-non-solvent” exchange rate which is attributed to the significant increase of viscosity of the coagulation bath. The separation performance of modified membranes for fractionation of thermomechanical pulp mill process water, for concentration and purification of hemicellulose for further processing was studied. It was found that membrane modification by Praestol 859 leads to 2–6 times increase of flux, increase of fouling recovery ratio and improvement of cleaning efficiency without decreasing membrane rejection with regard to hemicelluloses and lignin as reference components. An alternative approach for one-stage facile membrane modification during non-solvent induced phase separation (NIPS)-process using anionic high molecular polyacrylamide-based flocculant (AHMPF) was studied [21]. The effect of AHMPF concentration on the structure, composition and hydrophilicity of membranes was investigated. The separation and antifouling performance were evaluated during filtration of bovine serum albumin (BSA) solution and thermomechanical pulp mills process water (ThMP) in order to concentrate hemicellulose. The successful immobilization of AHMPF into the structure of membranes selective layer (not bottom layer). It was established that despite the similar rejections of hemicellulose and lignin, the modified membranes demonstrated 3–8 times higher flux and 2 times higher flux recovery ratio in ThMP ultrafiltration. The developed membrane was found to be highly efficient in hemicellulose concentration and purification in pulp industry. Another one-stage method for polysulfone (PSF) membrane modification was the addition of polyacrylic acid (PAA) to the coagulation bath during membrane preparation via non-solvent induced phase separation (NIPS) was proposed [22]. The effect of PAA concentration on the membrane structure, hydrophilicity, zeta potential, separation performance and antifouling stability in ultrafiltration of lysozyme, polyvinylpyrrolidone (PVP K-30) and humic acid model solutions as well as thermomechanical pulp mill process water was studied. It was revealed that pure water flux (PWF) decreased and lysozyme and PVP K-30 rejection increased with the increase in PAA concentration in the coagulation bath. It was found that membranes modified with PAA demonstrated better antifouling stability in ultrafiltration of humic acid solution and ThMP process water. Modified membranes were found to have higher flux, fouling recovery ratio and hemicelluloses rejection in ThMP process water ultrafiltration compared to the reference PSF membrane that allows application of these membranes for hemicelluloses concentration and purification. The study was further extended [22] by simultaneous addition of triblock copolymer polyethylene glycol-polypropylene glycol-polyethylene glycol (Synperonic F108) to the casting solution and addition of polyacrylic acid (PAA) to the coagulation bath is proposed for the first time. The addition of PAA into the coagulation bath was revealed to cause the formation of a thicker and denser selective layer with decreasing its pore size and porosity; according to the structural characterization, an interpolymer complex of the two additives was formed on the surface of the PSF membrane. Hydrophilicity of the membrane selective layer surface was shown to increase significantly. The selective layer surface charge was found to become more negative in comparison to the reference membrane. It was shown that PSF/Synperonic F108/PAA membranes are characterized by better antifouling performance in ultrafiltration of humic acid solution and ThMP process water. Membrane modification with PAA results in higher ThMP process water flux, fouling recovery ratio, and hemicellulose and total lignin rejection compared to the reference PSF/Synperonic F108 membrane. This suggests the possibility of applying the developed membranes for hemicellulose concentration and purification.

Overall, the work shows that for the successful integration of membrane processes in biorefineries both further understanding of membrane fouling and cleaning by advanced in-situ methods is required as well as the development of new low fouling membranes.

The following publications related to Subtask C were prepared in the duration of the Task:

[12] G. Rudolph, T. Virtanen, M. Ferrando, C. Güell, F. Lipnizki and M. Kallioinen: A review of in situ real-time monitoring techniques for membrane fouling in the biotechnology, biorefinery and food sectors, Journal of Membrane Science, 588, 2019, doi.org/10.1016/j.memsci.2019.117221.

[13] G. Rudolph, A. Hermansson, A.-S. Jönsson and F. Lipnizki: Investigating adsorptive membrane fouling of thermomechanical pulping process water with QCM-D. Separation and Purification Technology, (2020), https://doi.org/10.1016/j.seppur.2020.117578.

[14] G. Rudolph, H. Schagerlöf, K.B. Morkeberg Krog, A-S. Jönsson and F. Lipnizki: Investigations of Alkaline and Enzymatic Membrane Cleaning of Ultrafiltration Membranes Fouled by Thermomechanical Pulping Process Water Membranes 2018, 8*(4)*, 91. DOI: 10.3390/membranes8040091.

[15] T. Virtanen, A. Lopatina, B. Al-Rudainy, G. Rudolph, H. Schagerlöf, L. Puro, M. Kallioinen and F. Lipnizki: Analysis of ultrafiltration membrane fouling by Brunauer-Emmet-Teller nitrogen adsorption/desorption technique, Scientific Reports 10, 2020, 3427, doi.org/10.1038/s41598-020-59994-1.

[16] J. Thuvander, A. Zarebska, C. Helix-Nielsen and A.-S. Jönsson: Characterization of Irreversible Fouling after Ultrafiltration of Thermomechanical Pulp Mill Process Water, J. Wood Chem. Techn. 2018, 38*(3)*, 276–285. DOI:10.1080/02773813.2018.1454962.

[17] G. Rudolph, B. Al-Rudainy, J. Thuvander and A-S. Jönsson: Comprehensive Analysis of Foulants in an Ultrafiltration Membrane Used for the Treatment of Bleach Plant Effluent in a Sulfite Pulp Mill, Membranes 2021, 11(3), 201; https://doi.org/10.3390/membranes11030201.

[18] M. Zhou, H. Sandström, M. Belioka, T. Pettersson and T. Mattsson: Investigation of the cohesive strength of membrane fouling layers formed during cross-flow microfiltration: The effects of pH adjustment on the properties and fouling characteristics of microcrystalline cellulose. Chemical Engineering Research and Design, 149, 2019, 52-64.

[19] M. Zhou and T. Mattsson: Effect of crossflow regime on the deposit and cohesive strength of membrane surface fouling layers. Food and Bioproducts Processing, 115, 2019, 185-193.

[20] T. Hliavitskaya, T. Plisko, A. Bildyukevich, F. Lipnizki, G. Rodrigues, M. Sjölin: New PES-PRAESTOL 859 UF membranes for hemicellulose purification. Chemical Engineering Research and Design, 162 (2020), 187–199.

[21] T. Hliavitskaya, T. Plisko, S. Pratsenko, A. Bildyukevich, F. Lipnizki, G. Rodrigues, M. Sjölin: De-velopment of antifouling ultrafiltration PES membrane for concentration of hemicellulose. Journal of Applied Polymer Science. https://doi.org/10.1002/app.50316.

[22] K.S. Burts, T.V. Plisko, A.V. Bildyukevich, G. Rodrigues, M. Sjölin, F. Lipnizki and M. Ulbricht: Development of polysulfone ultrafiltration membranes with enhanced antifouling performance for the valorisation of side streams in the pulp and paper industry. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 632 (2022), 127742.

[23] K.S. Burts, T.V. Plisko, M. Sjölin, G. Rodrigues, A.V. Bildyukevich, F. Lipnizki and M. Ulbricht. Development of antifouling polysulfone membranes by synergistic modification with two different additives in casting solution and coagulation bath: Synperonic F108 and polyacrylic acid, Materials 2022, 15(1), 359; https://doi.org/10.3390/ma15010359.

4.3 Subtask D: Pretreatment of biomass process streams before membrane separation

The aim of this subtask was to map different pre-treatment before membrane separation processes with reference to the biomass process streams. The subtask was lead by Mihail Barboiu, Institut Européen des Membranes, France addressing the following aspects:

- Pre-treatment is often the key for the successful integration of membrane processes in biorefineries
- Methods for selecting optimal pre-treatment
- Integration and optimization of pre-treatment methods and membrane processes.

In duration of the Task, it turned out that Subtask D had significant overlaps with Subtask A: Separation in biorefineries and Subtask B: Integration and optimization of membrane processes in biorefineries. Thus, Subtask D had no dedicated projects.

4.4 Subtask E: Emerging membrane processes

In recent years several emerging membrane processes became commercially available. To gain further understanding on these processes and their potentials Subtask E headed Judith Buchmaier, Institute for Sustainable Technologies (AEE INTEC), Austria addressing the following aspects:

- The potential for emerging membrane technologies in biorefineries is so far not systematically mapped.
- VP and PV have some niche applications in e.g. ethanol producing biorefineries but the overall potential is relative unexplored.
- FO and MD have some potential in biorefineries but process integration and benchmarking with conventional technologies has to be addressed.

The subtask focused on the development of an integration guideline and two projects related to emerging membrane process – forward osmosis and pervaporation.

Guideline for the integration of emerging membrane separation processes in biorefineries

A key output of this subtask was the “Guideline for the integration of emerging membrane separation processes in biorefineries for research, industry and decision-makers” completed by AEE (Austria) based on the meetings and mapping done within the subtask. The objective of the guideline prepared by AEE (Austria) was to give an overview of the emerging membrane technologies, map the actions done so far and include know-how transfer within the international consortium, including integration concepts of membrane applications in biorefineries, such pre-treatment and cleaning approaches. The aim of the guideline is to support and enable the integration of potential membrane technologies in biorefining industry. This guidance gives possible integration concepts of membranes in biorefineries as well as recommendations for R&D, technology development, research, industry and decision-maker with focus on forward osmosis (FO), membrane distillation (MD), liquid membrane permeation (LMP) and pervaporation (PV).

Forword osmosis project

A project on process intensification of sulfate pulp production with lignin recovery by pressure-assisted forward osmosis was completed at Lund University (Sweden) [25]. The project revealed that forward osmosis was not suitable for this application due to high osmotic of the feed from the sulphate pulp production. However, it was shown that conventional pressure driven nanofiltration is suitable for this application.

Pervaporation project.

The downstream processing of ABE fermentation broth with pervaporation was studied in project under the participation of Lund University [26]. In this work, results of the application of both hydrophobic and hydrophilic commercial membranes during the pervaporation of ABE aqueous mixtures were investigated and presented. Hydrophobic pervaporation experiments were performed using ABE-water mixtures containing 0–5 wt% of organics in feed, using commercial membranes: POMS, PEBAX, and Pervap™4060. Separation factor and Pervaporation Separation Index were employed to discuss hydrophobic pervaporation results. Pervap™4060 membrane revealed the best separation performance in the removal of ABE components from diluted aqueous mixtures mimicking the fermentation broth, resulting in two-phase permeate containing ca. 34 wt% of organics. The subsequent liquid-liquid phase separation resulted in the organic phase containing 62 wt% of ABE. Hydrophilic pervaporation experiments were performed in contact with ABE-water system initially comprising 38 wt% of water applying both the Pervap™4100 PVA based polymeric membrane and modified silica ceramic one. Application of hydrophilic membranes allowed for the complete dewatering of ABE-water mixtures. Eventually, a combination of membrane separation processes (microfiltration, hydrophobic pervaporation, hydrophobic thermos-pervaporation, membrane distillation, and hydrophilic pervaporation) enhanced by the liquid-liquid phase separation was suggested for the recovery and dehydration of ABE aqueous mixture.

The guideline developed and projects in this subtask underlined the potential of emerging membrane processes in different concepts of biorefineries.

The following publications related to Subtask E were prepared in the duration of the Task:

[24] J. Buchmaier, B. Muster, E. Guillen, S. Meitz, Membranes in Biorefineries - Guideline for the integration of emerging membrane separation processes in biorefineries for research, industry and decision-makers, AEE, Austria.

[25] Process intensification of sulfate pulp production with lignin recovery by pressure-assisted forward osmosis), Project No. 47504-1, funded by Energimyndigheten.

[26] K. Knozowska, A. Kujawska, G. Li, J. Kujawa, M. Bryjak, W. Kujawski, F. Lipnizki, L. Ahrné, J.K. Kujawski: Membrane assisted processing of acetone, butanol, and ethanol (ABE) aqueous streams. Chemical Engineering and Processing - Process Intensification, 166 (2021) http://doi.org/10.1016/j.cep.2021.108462.

4.5 Subtask F: Water and wastewater treatment in biorefineries

In this subtask, the focus was on the water loop of biorefineries since membrane processes are key processes in water preparation and wastewater treatment. The subtask was led by Morten Lykkegaard Christensen, Aalborg University (AAU), Denmark based on the following aspects:

- The water loop is a key loop in biorefineries
- The ideal scenario is the biorefinery with a closed water loop.
- Membrane processes can be part of the in-take water preparation and wastewater treatment.
- Water recovery in processes and recycling of water from the wastewater treatment plant can be achieved with the support of membrane processes.

A key project related to the subtask was the Danish KLIVER project

KLIVER project

The KLIVER project focused on the production and purification of volatile fatty acids from wastewater as a resource for biomass substrate/energy source and was carried out by Aalborg University and DTU (both, Denmark). The goal of this project was to develop a climate friendly wastewater treatment concept by investigating to what extent primary sludge can be hydrolyzed to create an internal carbon source that can be used for both biogas production, nitrogen and phosphorus removal.

The project in this subtask shows the potential membrane technology for water and wastewater treatment but also highlights that the real development potential in this area is in water and resource recovery.

5. CONCLUSION AND OUTLOOK

The interest in the work of the Task is very high which is documented in the increasing number of participants during this period of the Task and application for a continuation of the work will be submitted.

The Task provided an excellent platform with meetings, workshops and dissemination activities for IETS members interested in membrane processes for biorefineries. The discussion on an extension of this Task started during the last Task Meeting showed that there is large interest in continuation of the Task activities. We recommend therefore to consider a continuation of the current Task as Task “Membranes in biorefinery”. It was also realised that some subtasks of the current Task require some adjustment by focus on the latest research trends. Furthermore, the interactions with other Tasks, i.e. Task XI Industry-based biorefineries towards sustainability and Task XIX Electrification in Industry should be intensified.

6. SELECTED PUBLICATIONS

Article

2022

M. Battestini Vives, J. Thuvander, A. Arkell and F. Lipnizki: Low-molecular-weight lignin recovery with nanofiltration in the kraft pulping process. Membranes, 2022, 12, 310. https://doi.org/10.3390/membranes12030310. (Subtask B)

M. Sjölin, M. Sayed, J. Thuvander, F. Lipnizki, R. Hatti-Kaul, O. Wallberg: Effect of membrane purification and concentration of sucrose in sugar beet molasses for the production of 5-Hydroxymethylfurfural, Chemical Engineering Research and Design, https://doi.org/10.1016/j.cherd.2022.01.007. (Subtask A)

2021

K.S. Burts, T.V. Plisko, M. Sjölin, G. Rodrigues, A.V. Bildyukevich, F. Lipnizki and M. Ulbricht. Development of antifouling polysulfone membranes by synergistic modification with two different additives in casting solution and coagulation bath: Synperonic F108 and polyacrylic acid, Materials 2022, 15(1), 359; https://doi.org/10.3390/ma15010359. (Subtask C)

K.S. Burts, T.V. Plisko, A.V. Bildyukevich, G. Rodrigues, M. Sjölin, F. Lipnizki and M. Ulbricht: Development of polysulfone ultrafiltration membranes with enhanced antifouling performance for the valorisation of side streams in the pulp and paper industry. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 632 (2022), 127742. (Subtask C)

F. Lipnizki, G. Rudolph, J. Thuvander, B. Al-Rudainy and M. Battestini Vives: Anwendungspoten-tial von Membranprozessen im Konzept der Lignocellulose-Bioraffinerien (Application potential of membrane processes in the concept of lignocellulose biorefineries). Chemie Ingenieur Technik, 93 (2021), http://doi.org/10.1002/cite.202100018. (Subtask B)

2020

K. Knozowska, A. Kujawska, G. Li, J. Kujawa, M. Bryjak, W. Kujawski, F. Lipnizki, L. Ahrné, J.K. Kujawski: Membrane assisted processing of acetone, butanol, and ethanol (ABE) aqueous streams. Chemical Engineering and Processing - Process Intensification, 166 (2021) http://doi.org/10.1016/j.cep.2021.108462. (Subtask E)

T. Hliavitskaya, T. Plisko, S. Pratsenko, A. Bildyukevich, F. Lipnizki, G. Rodrigues, M. Sjölin: Development of antifouling ultrafiltration PES membrane for concentration of hemicellulose. Journal of Applied Polymer Science. https://doi.org/10.1002/app.50316. (Subtask C)

T. Hliavitskaya, T. Plisko, A. Bildyukevich, F. Lipnizki, G. Rodrigues, M. Sjölin: New PES-PRAESTOL 859 UF membranes for hemicellulose purification. Chemical Engineering Research and Design, 162 (2020), 187–199. (Subtask C)

G. Rudolph, A. Hermansson, A.-S. Jönsson and F. Lipnizki: Investigating adsorptive membrane fouling of thermomechanical pulping process water with QCM-D. Separation and Purification Technology, (2020), https://doi.org/10.1016/j.seppur.2020.117578. (Subtask C)

A.V. Bildyukevich, T.V. Plisko, F. Lipnizki, S.A. Pratsenko: Correlation between membrane surface properties, polymer nature and fouling in skim milk ultrafiltration. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 605 (2020), 125387. (Subtask C)

T. Virtanen, A. Lopatina, B. Al-Rudainy, G. Rudolph, H. Schagerlöf, L. Puro, M. Kallioinen and F. Lipnizki: Analysis of ultrafiltration membrane fouling by Brunauer-Emmet-Teller nitrogen adsorption/desorption technique, Scientific Reports 10, 2020, 3427, doi.org/10.1038/s41598-020-59994-1. (Subtask C)

M. Sjölin, J. Thuvander, O. Wallberg and F. Lipnizki: Purification of sucrose in sugar beet molasses by utilizing ceramic nanofiltration and ultrafiltration membranes. Membranes, 2020, 10, 5. doi.org/10.3390/membranes10010005. (Subtask A)

2019

B. Al-Rudainy, M. Galbe, F. Lipnizki and O. Wallberg. Galactoglucomannan recovery with hydrophilic and hydrophobic membranes: Process performance and cost estimations. Membranes, 2019, 10:9(8):99. doi.org/10.3390/membranes9080099. (Subtask B)

G. Rudolph, T. Virtanen, M. Ferrando, C. Güell, F. Lipnizki and M. Kallioinen: A review of in situ real-time monitoring techniques for membrane fouling in the biotechnology, biorefinery and food sectors, Journal of Membrane Science, 588, 2019, doi.org/10.1016/j.memsci.2019.117221. (Subtask C)

J. Thuvander, F. Lipnizki and A.-S. Jönsson: On-site recovery of hemicelluloses from thermomechanical pulp mill process water by microfiltration and ultrafiltration. Journal of Wood Chemistry and Technology, 39, 2019, doi: 10.1080/02773813.2019.1565865. (Subtask B)

M. Zhou, H. Sandström, M. Belioka, T. Pettersson and T. Mattsson: Investigation of the cohesive strength of membrane fouling layers formed during cross-flow microfiltration: The effects of pH adjustment on the properties and fouling characteristics of microcrystalline cellulose. Chemical Engineering Research and Design, 149, 2019, 52-64. (Subtask C)

D. Humpert, M. Ebrahimi, A. Stroh and P. Czermak Recovery of lignosulfonates from spent sulfite liquor using ceramic hollow-fiber membranes. Membranes, 2019, 9, 45; doi:10.3390/membranes9040045. (Subtask B)

M. Zhou and T. Mattsson: Effect of crossflow regime on the deposit and cohesive strength of membrane surface fouling layers. Food and Bioproducts Processing, 115, 2019, 185-193. (Subtask B)

N.T. Faria, S. Marques, F. C. Ferreira and C. Fonseca, Production of xylanolytic enzymes by Moesziomyces spp. using xylose, xylan and brewery’s spent grain as substrates, New Biotechnology, 49, 2019, 137-143, ISSN 1871-6784, doi: 10.1016/j.nbt.2018.11.001. (Subtask B)

M.V Santos., N.T. Faria, C. Fonseca, F.C. Ferreira, Production of mannosylerythritol lipids from lignocellulose hydrolysates: tolerance thresholds of Moesziomyces antarcticus to inhibitors. 94 (4), 2019, 1064-1072, J. Chem. Technol. Biotechnol. ISSN: 1097-4660, ISSN 0268-2575. doi:10.1002/jctb.5853. (Subtask B)

Conferences

2022

M. Sjölin, M. Sayed, J. Thuvander, R. Hatti-Kaul, O. Wallberg, Frank Lipnizki: Impact of sugar beer molasses purification by ultra-and nanofiltration on the 5-Hydroxymethylfurfural production, Filtech 2022, 2022, Cologne, Germany. (Subtask A)

2021

K.S. Burts, T.V. Plisko, A.V. Bildyukevich, G. Rodrigues, M. Sjölin, F. Lipnizki and M. Ulbricht: Development of polysulfone ultrafiltration membranes with enhanced antifouling performance for the valorisation of side streams in the pulp and paper industry, Euromembrane 2021, Copenhagen, Denmark. (Subtask C)

M. Battestini Vives, J. Thuvander, A. Arkell and F. Lipnizki: From lab to pilot scale: Lignin recovery with nanofiltration in the kraft pulping process, Euromembrane 2021, Copenhagen, Denmark. (Subtask B)

G. Rudolph, A.-S. Jönsson and F. Lipnizki: Ultrafiltration of process streams from lignocellulosic biorefineries: Insights on membrane fouling and cleaning, Euromembrane 2021, Copenhagen, Denmark. (Subtask C)

M. Sjölin, S. Herrlin, O. Wallberg, J. Thuvander and F. Lipnizki: Purification of galactoglucoman-nan in the liquid fraction from steam pretreatment of soft wood using ultrafiltration membranes, Euromembrane 2021, Copenhagen, Denmark. (Subtask A)

M. Battestini Vives, J. Thuvander, A. Arkell and F. Lipnizki, Scaling up nanofiltration of kraft black liquor for lignin recovery, 18th Network Young Membrains Meeting, 2021, Lund, Sweden. (Subtask B)

M. Battestini Vives, J. Thuvander, A. Arkell and F. Lipnizki: Producing biofuel from lignin: How close are we? PhD Conference on Sustainable Development, 2021, Lund, Sweden. (Subtask B)

F. Lipnizki, J. Thuvander, G. Rudolph and M. Battestini Vives: Anwendungspotential von Membranprozessen im Konzept Lignocelluloser-Bioraffinerien, DGMT Jahrestagung 2021, "Membranen zum Schutz von Klima und Ressourcen", Germany. (Subtask B)

2020

F. Lipnizki, J. Thuvander, B. Al-Rudainy, A. Arkell, O. Wallberg and A.-S. Jönsson: New membrane-based concepts for ligno-cellulosic biorefineries: Status and challenges, ICOM 2020, 2020, London, UK. (Subtask B)

T.V. Plisko, K.S. Burts, M. Sjölin, G. Rodrigues, M. Mateus, A.V. Bildyukevich, M. Ulbricht and F. Lipnizki: Development of pH-sensitive membranes with enhanced antifouling performance for the valorisation of side streams in the pulp industry, ICOM 2020, 2020, London, UK (Keynote). (Subtask C)

M. Battestini Vives, K. Li, J. Thuvander, C. Hulteberg, A. Arkell and F. Lipnizki: Performance of nanofiltration membranes for the recovery of lignin from kraft black liquor in the production of renewable fuels, ICOM 2020, 2020, London, UK. (Subtask B)

M. Sjölin, J. Thuvander, F. Lipnizki and O. Wallberg: The effect of ultrafiltration and nanofiltration membranes upstream a 5-Hydroxymethylfurfural production process from sugar beet molasses, ICOM 2020, 2020, London, UK. (Subtask A)

G. Rudolph, A.-S. Jönsson and F. Lipnizki: Studying membrane fouling in lignocellulosic biorefiner-ies with QCM-D, ICOM 2020, 2020, London, UK. (Subtask C)

G. Rudolph, T. Virtanen, H. Schagerlöf, L. Puro, M. Kallioinen and F. Lipnizki: Brunauer-Emmett-Teller analysis – a suitable method for membrane fouling in lignocellulosic biorefineries? ICOM 2020, 2020, London, UK. (Subtask C)

F. Lipnizki, J. Thuvander, B. Al-Rudainy, A. Arkell, O. Wallberg and A.-S. Jönsson: New membrane-based concepts for ligno-cellulosic biorefineries: Status and challenges, ICOM 2020, 2020, London, UK. (Subtask B)

2019

F. Lipnizki, G. Rudolph and J. Thuvander: Membrane processes in ligncellulosic biorefineries: Status, potential and challenges. *PERMEA 2019*, 2019, Budapest, Hungary. (Subtask B)

F. Lipnizki, J. Thuvander and G. Rudolph: Membrane opportunities in lignocellulosic biorefineries, *Engineering with Membranes*, 2019, Båstad, Sweden. (Subtasks B and C)

G. Rudolph and F. Lipnizki: New developments in fouling and cleaning of membrane processes in lignocellulosic biorefineries. *Treesearch Progress Conference*, 2019, Norrköping, Sweden. (Subtask C)

M. Sjölin, J. Thuvander, O. Wallberg and F. Lipnizki: Purification and retention of sucrose in sugar beet molasses by utilizing ceramic nanofiltration membranes, *Engineering with Membranes*, 2019, Båstad, Sweden. (Subtask A)

G. Rudolph, T. Virtanen, F. Lipnizki and M. Kallioinen: In situ real-time monitoring techniques for membrane fouling in food, biorefinery and biotechnology industries, *Engineering with Membranes*, 2019, Båstad, Sweden. (Subtask C)

Editions

F. Lipnizki and S. Luque: Engineering with Membranes – Membranes for a sustainable future, Conference proceedings, Båstad, Sweden, 2019. (Subtasks A to F)

Books

F. Lipnizki, J. Thuvander and G. Rudolph: Membrane processes and applications for biorefineries. In: Membranes in Environmental Applications by A. Basile, A. Figoli and Y. Li, Elsevier B.V., Amsterdam, 2019. (Subtasks A – F)

Reports

J. Buchmaier, B. Muster, E. Guillen, S. Meitz , Membranes in Biorefineries - Guideline for the integration of emerging membrane separation processes in biorefineries for research, industry and decision-makers, AEE, Austria. (Subtask E)

ABOUT THE TCP ON INDUSTRIAL ENERGY-RELATED TECHNOLOGIES AND SYSTEMS (IETS TCP)

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