

# Oscillatory flow reactors as intensification approach in circular economy

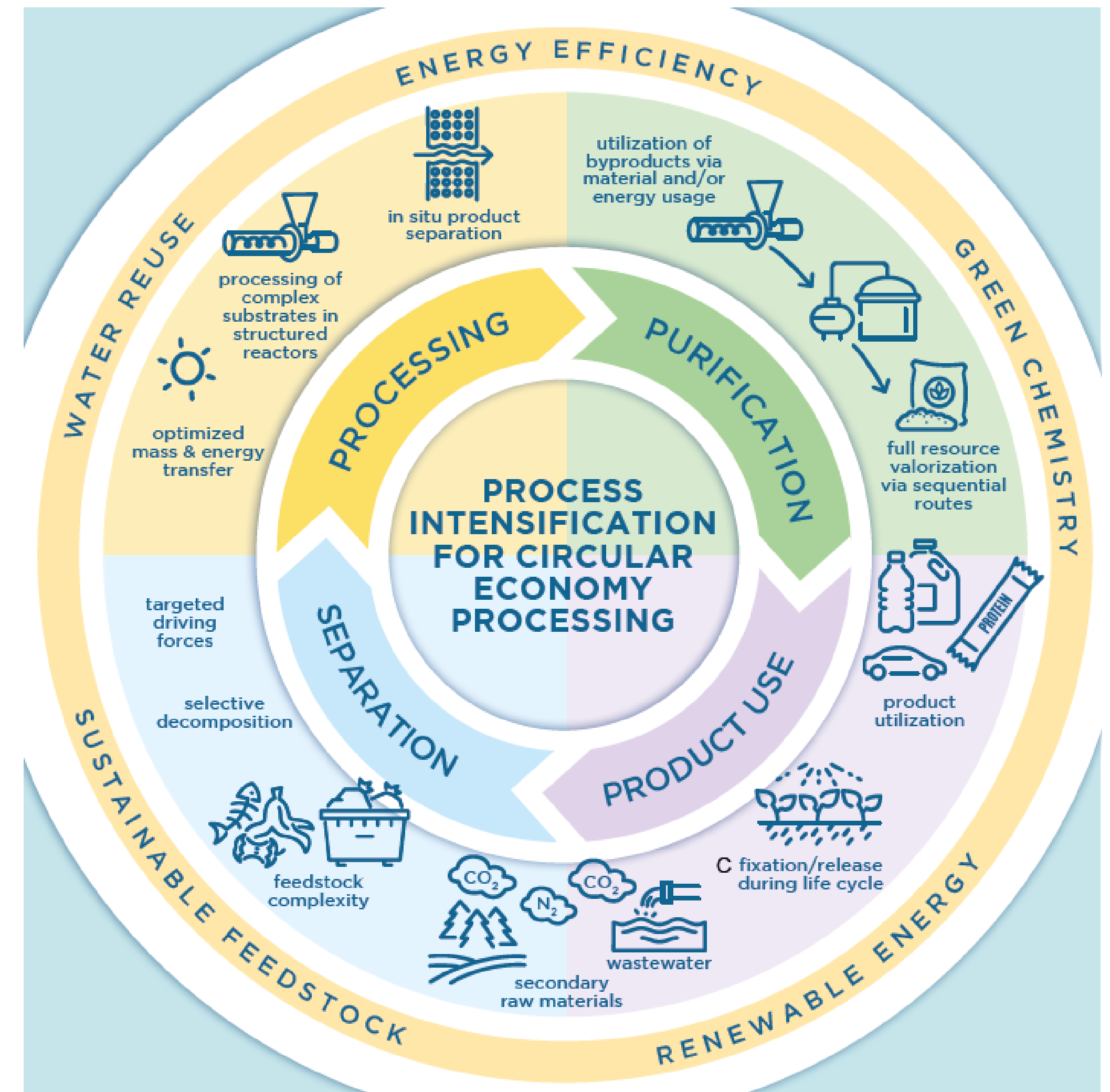
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Bettina Muster-Slawitsch

Judith Buchmaier, Sarah Meitz, Theresa Plesch, Philipp Petermeier, Mauricio Pane, Christoph Höfer, Christian Jeges, Lisa Sullmann, Maximilian Pöchtrager, Daniel Rüdisser

# Process Intensification for circular economy

- Processing complex media
- While CO<sub>2</sub> footprint reduces with residues as substrates, **energy demand at local sites can significantly increase due to more complex processing**
- Process and energy efficiency, renewable energy integration
- „Produce much more with much less“ → simple processes, direct use of slurry residues
- Valuable recovery, cascading pathways for optimized use of resources
- minimized follow-up costs!



# Energy efficiency in circular economy

- European target on energy efficiency 2030 – 4%/a (currently 1.4%/a)

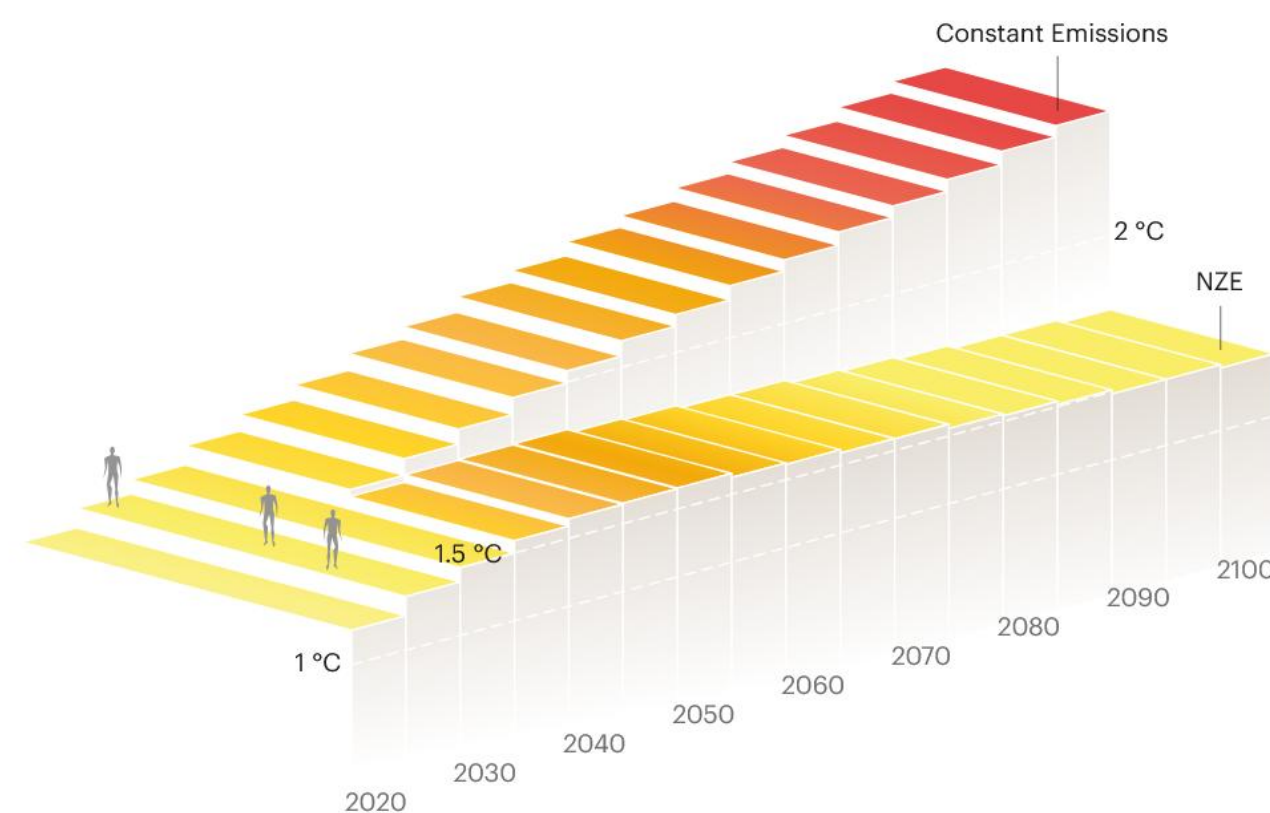
at least 11.7%  
energy efficient target

763 Mtoe  
final energy  
consumption

992.5 Mtoe  
primary energy  
consumption

[https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-targets\\_en#ref-2030-energy-efficiency-target](https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-targets_en#ref-2030-energy-efficiency-target)

## Net Zero Emissions Scenario IEA: doubling efficiency and tripling renewables capacity



*Thematic Roadmap: **Energy for Circular Economy** (innoenergy, 2023)*

*besides the targets → no chapter, no data, no measures neither recommendations for energy efficiency*

<https://www.iea.org/reports/world-energy-outlook-2025/net-zero-emissions-by-2050>

# Focus of our research group

Solar photoreactors

Bio-Processing

Ind. Water Treatment

NH<sub>4</sub>/NH<sub>3</sub> Recovery

Peat Substitution

Plastics Recycling



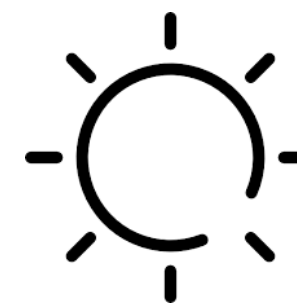
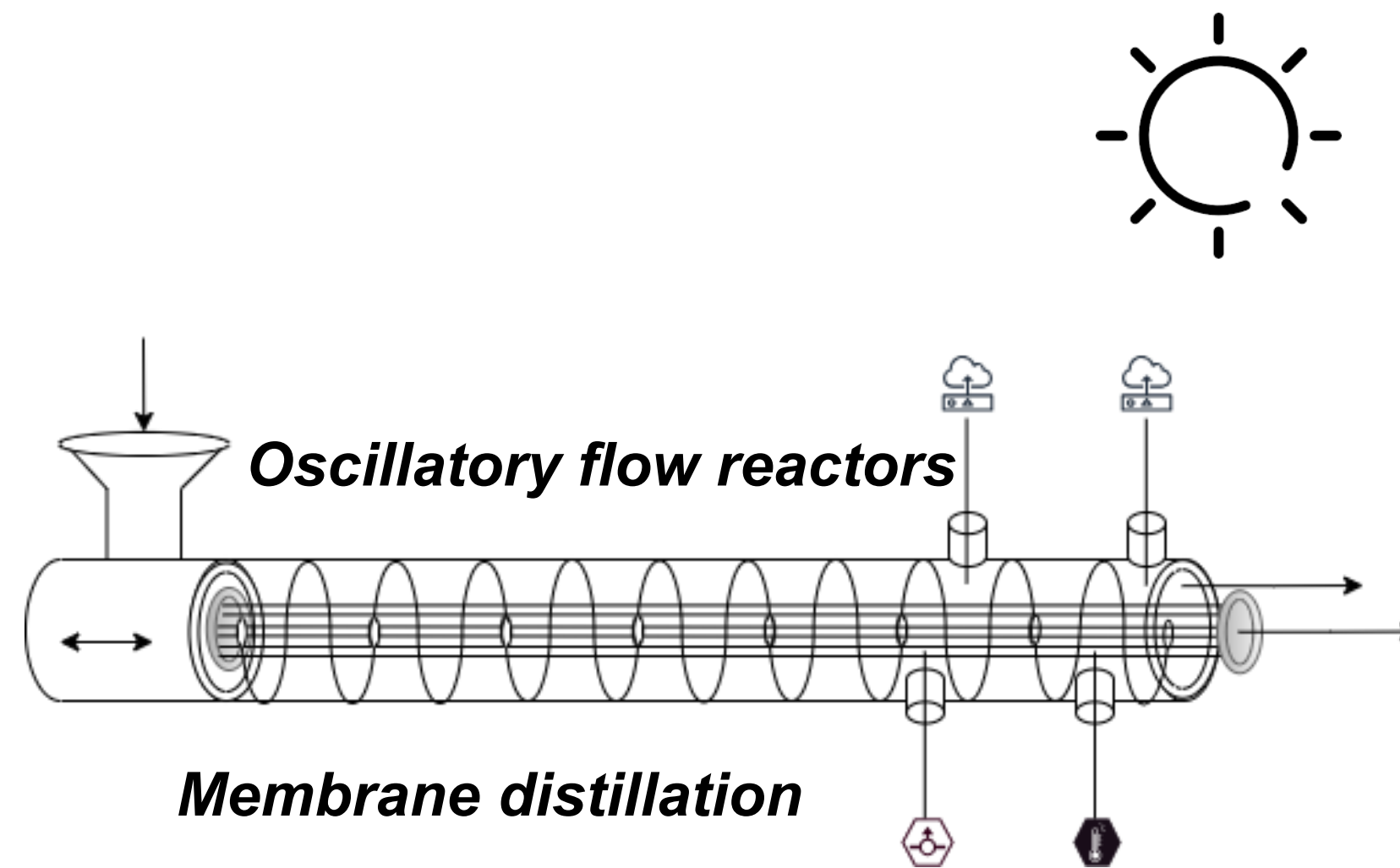
©istock/AEE INTEC



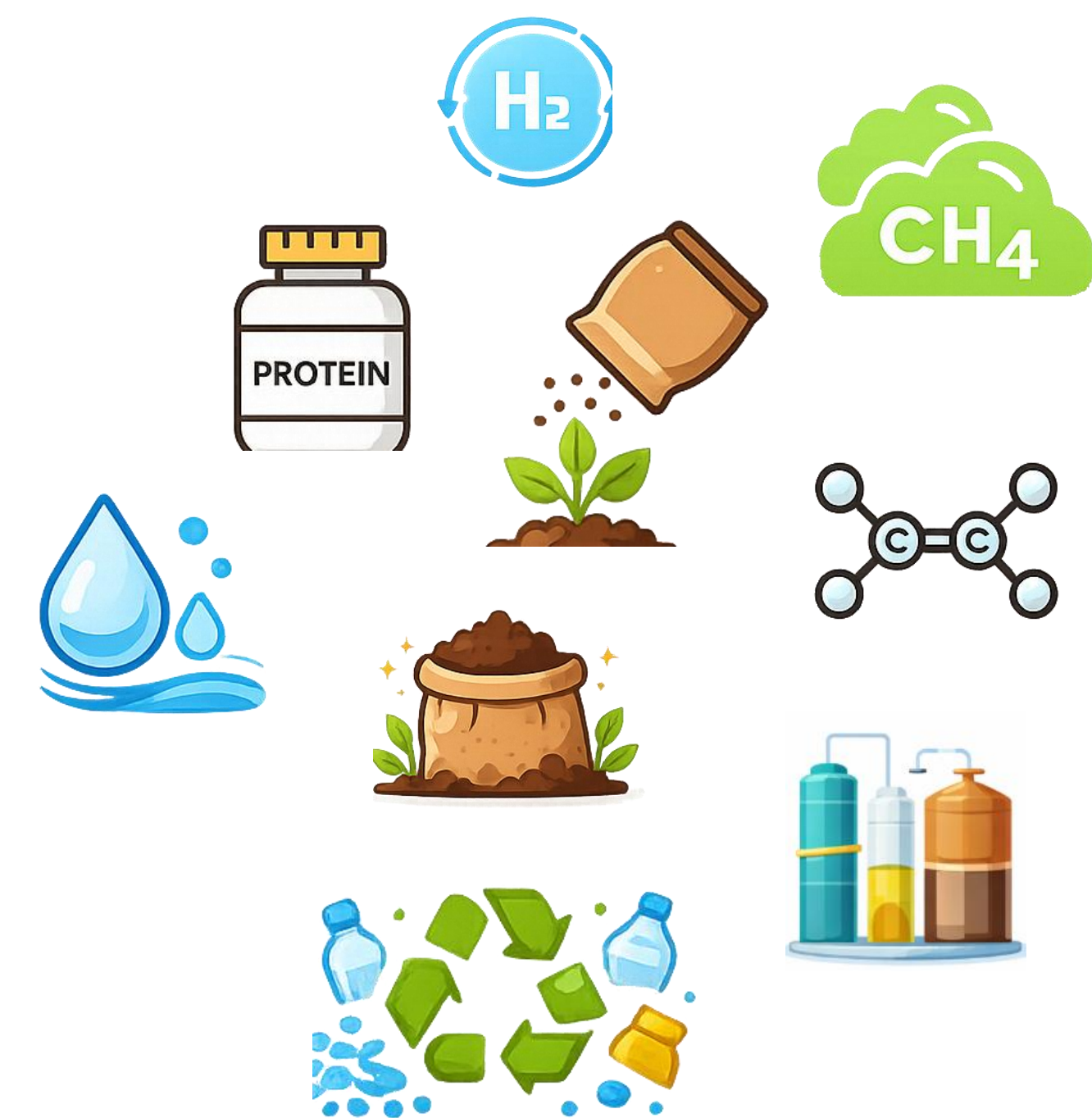
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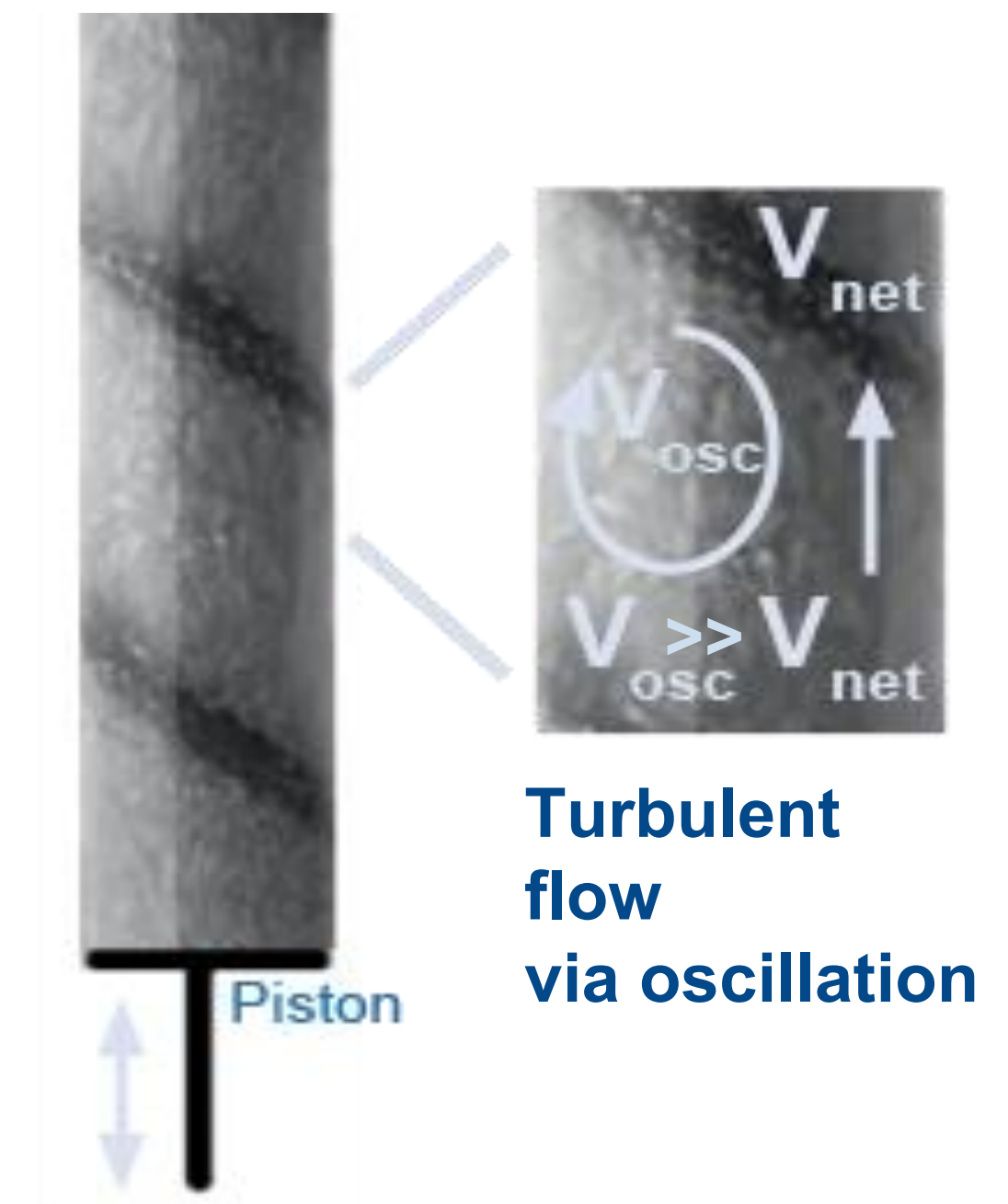


*Residence time, mixing, continuous processing, structured processes, intensification of driving forces, in-situ product recovery, reduction of solvents/chemicals/catalysts*



# Oscillatory Flow Reactors

- Oscillatory flow reactor = tubular reactors with baffles; oscillation of fluid; additional net flow possible
- Particle motion decoupled from net-flow velocity
- Advantages:
  - ideal mixing
  - **High solid concentrations** possible [→ proven in AEE INTEC projects for biobased reactions ]
  - Good process controllability; continuous processing
  - Very low net flow possible (mixing via oscillations)  
→ at **long residence times** short reactor lengths; „batch to conti“
  - High mass transfer (enhanced reaction performance, reduction of reaction times, reduced input of reagents)
  - low energy intensity (high energy transfer rates due to turbulent motion; oscillation energy < 0.4 Wh/kg for thick slurry)



# Oscillatory Flow Characterisation

$$Re_n = \frac{\rho u D}{\mu}$$

$$Re_o = \frac{\rho 2\pi f x_o D}{\mu}$$

$$\Psi = \frac{Re_o}{Re_n}$$

## Dimensionless numbers

**Reynolds number:** ratio of inertial to viscous forces in the fluid, determine turbulent and laminar flow regimes

- **Net-flow Reynolds number ( $Re_n$ )**, depends on
  - $u$  - superficial velocity (m/s),
  - $\rho$  - fluid density (kg/m<sup>3</sup>),
  - $D$  - inner diameter of the tube (m), and
  - $\mu$  - dynamic viscosity of the fluid (Pa·s).
- **Oscillatory Reynolds number ( $Re^o$ )** - when oscillatory motion is introduced on the net flow
  - $f$  - oscillation frequency (Hz)
  - $x_o$  - oscillation amplitude (m).
- **Velocity ratio ( $\psi$ )**, provides insight into the plug-flow characteristics of the system.

## Geometry

- $D$  (tube ID) [m]
- $A = \pi D^2/4$  [m<sup>2</sup>]
- $Z$  (active length) [m]
- Baffle/constriction details

## Fluid / slurry

- $\rho$  density [kg·m<sup>-3</sup>]
- $\mu$  dynamic viscosity [Pa·s]

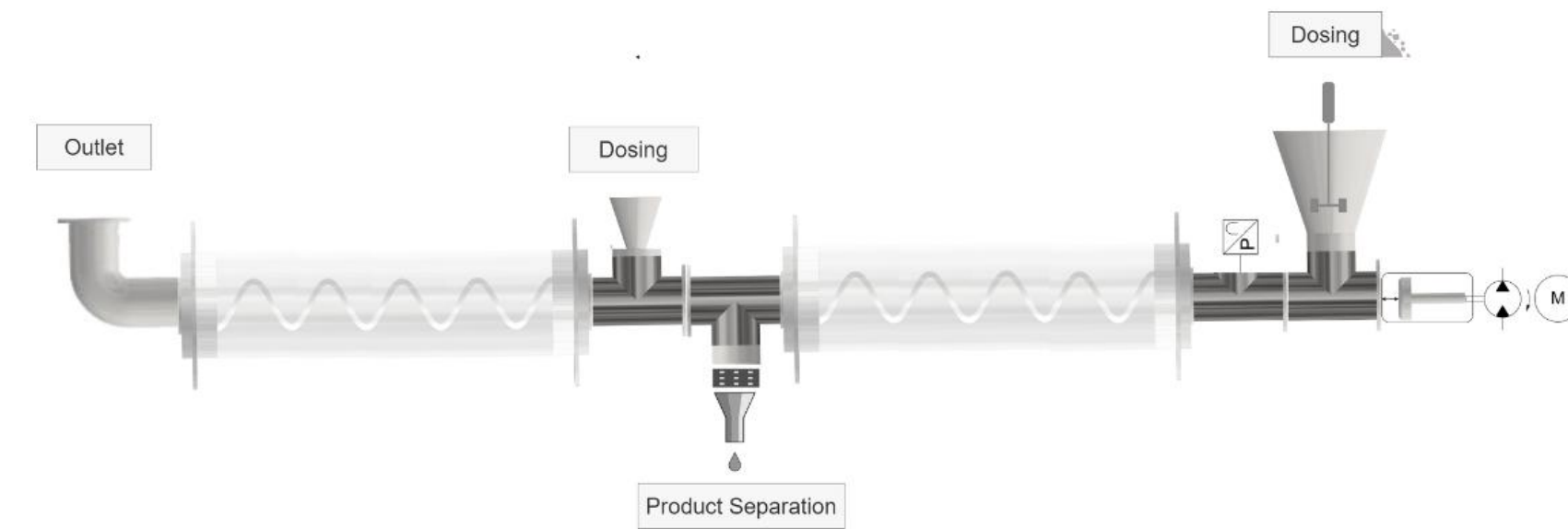
## Operating conditions

- $Q_n$  net flow rate [m<sup>3</sup>·s<sup>-1</sup>]
- $x_o$  amplitude [m]
- $f$  frequency [Hz]

# Applications

Solution technology for continuous mashing process

In-situ product removal during enzymatic cellulose hydrolysis

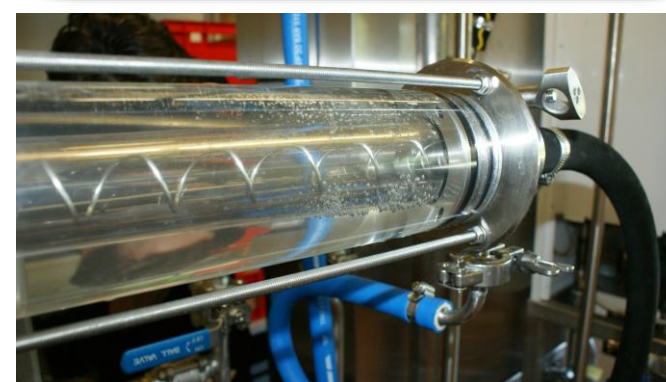
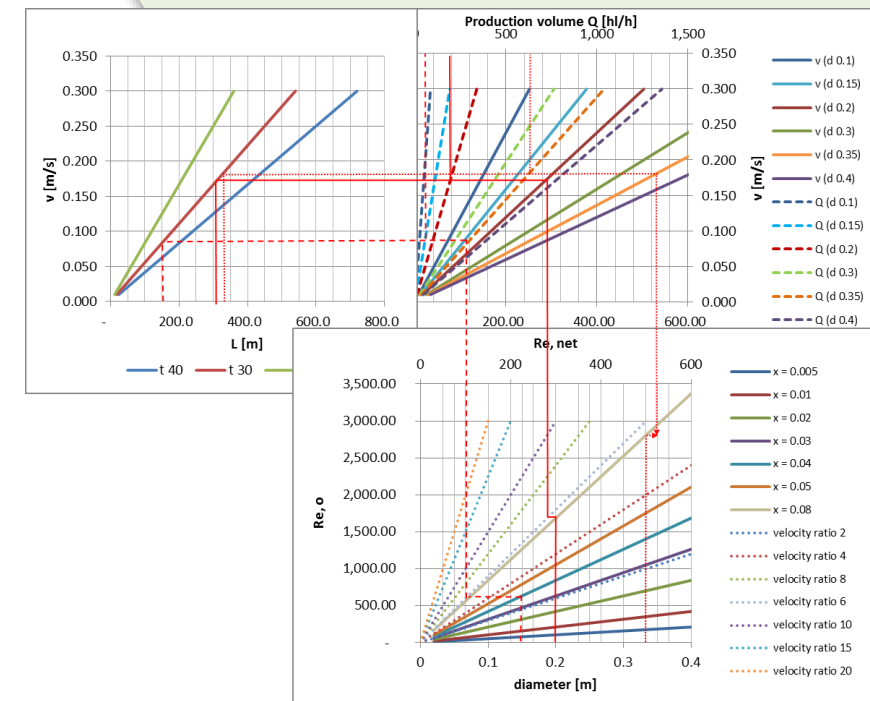
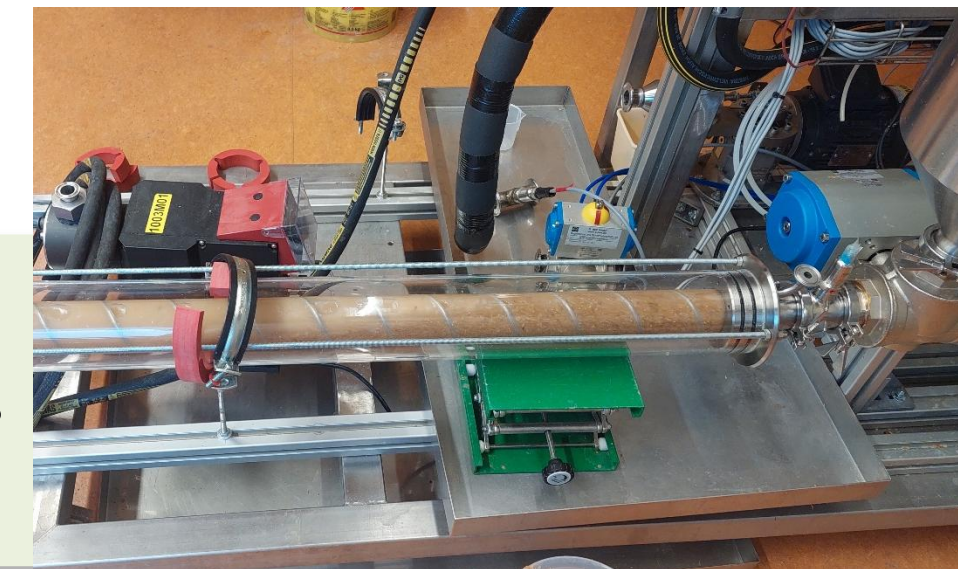


Continuous enzymatic cellulose hydrolysis

Protein hydrolysis from food processing residues

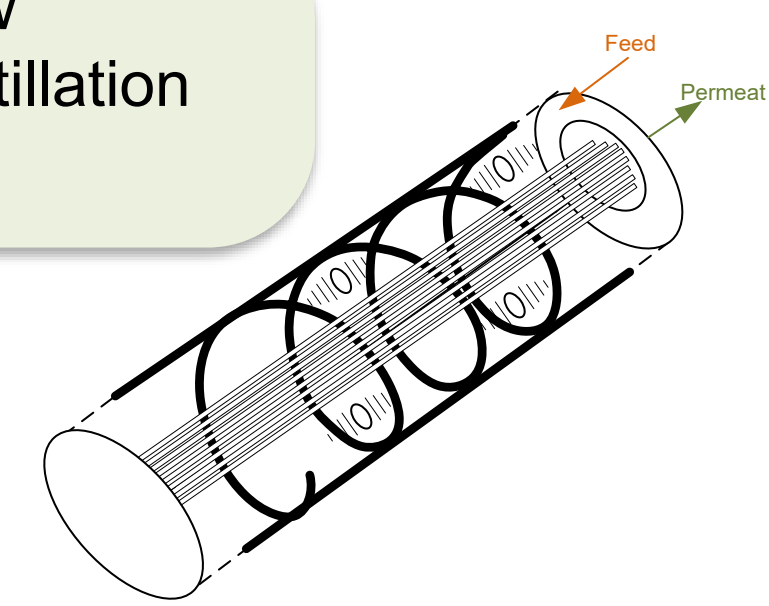
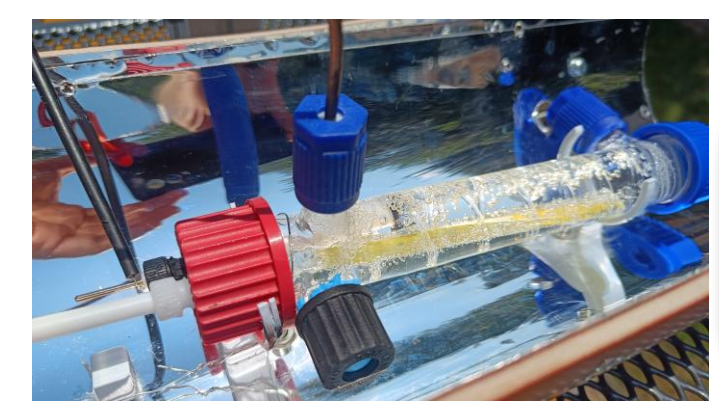


First scaling protein hydrolysis



Oscillatory flow membrane distillation

Oscillatory flow photoelectrochemical reactors



OBR Betrieb für Membrandestillation mit Hohlfasermödule (O-MD)

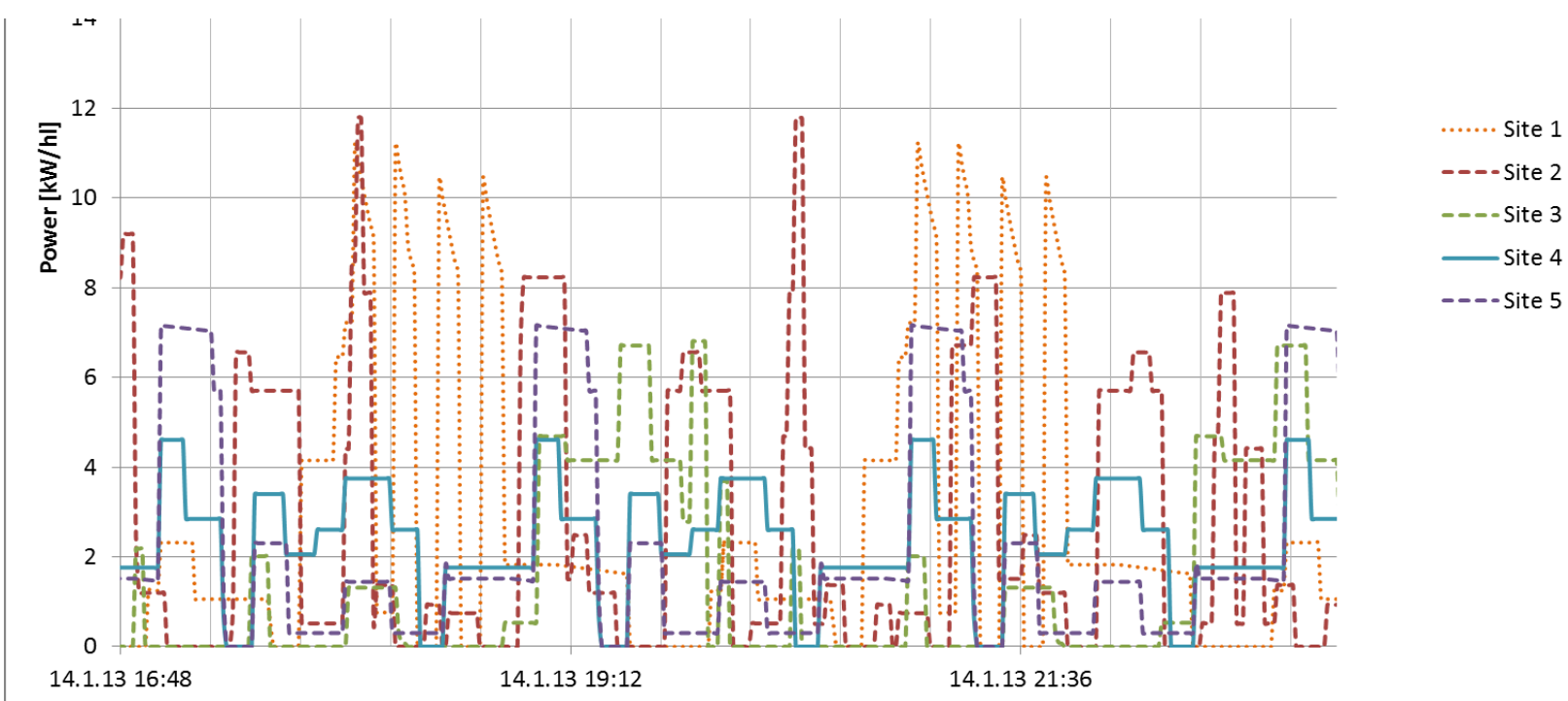
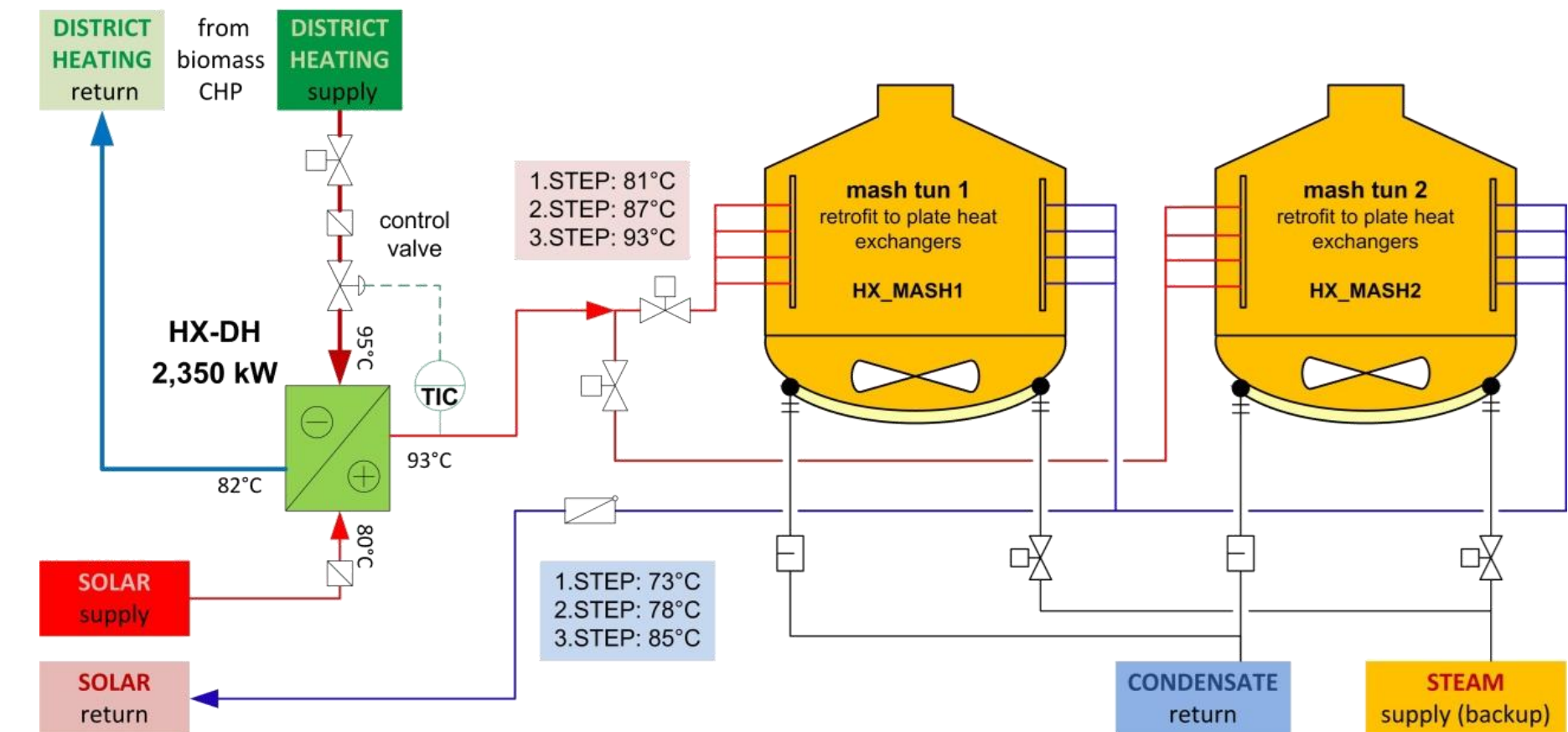
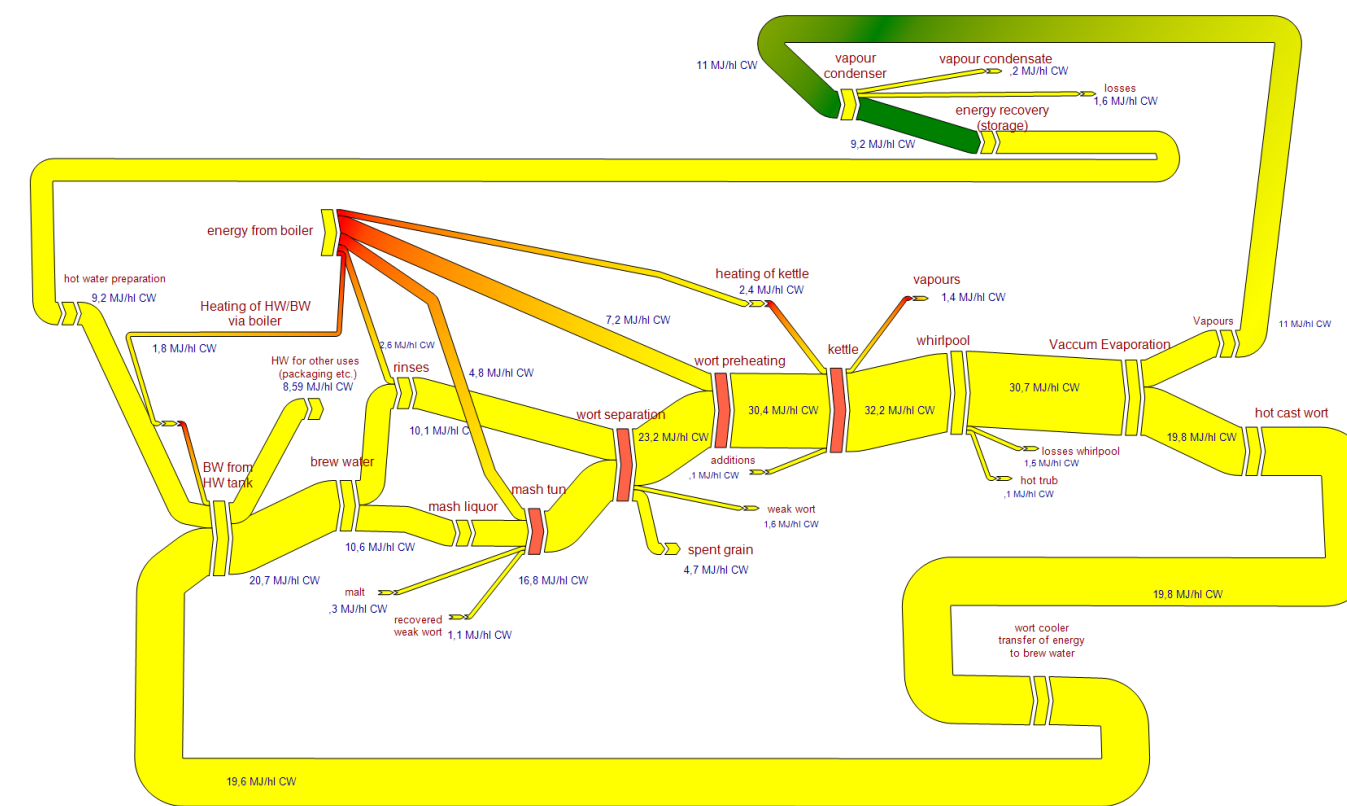
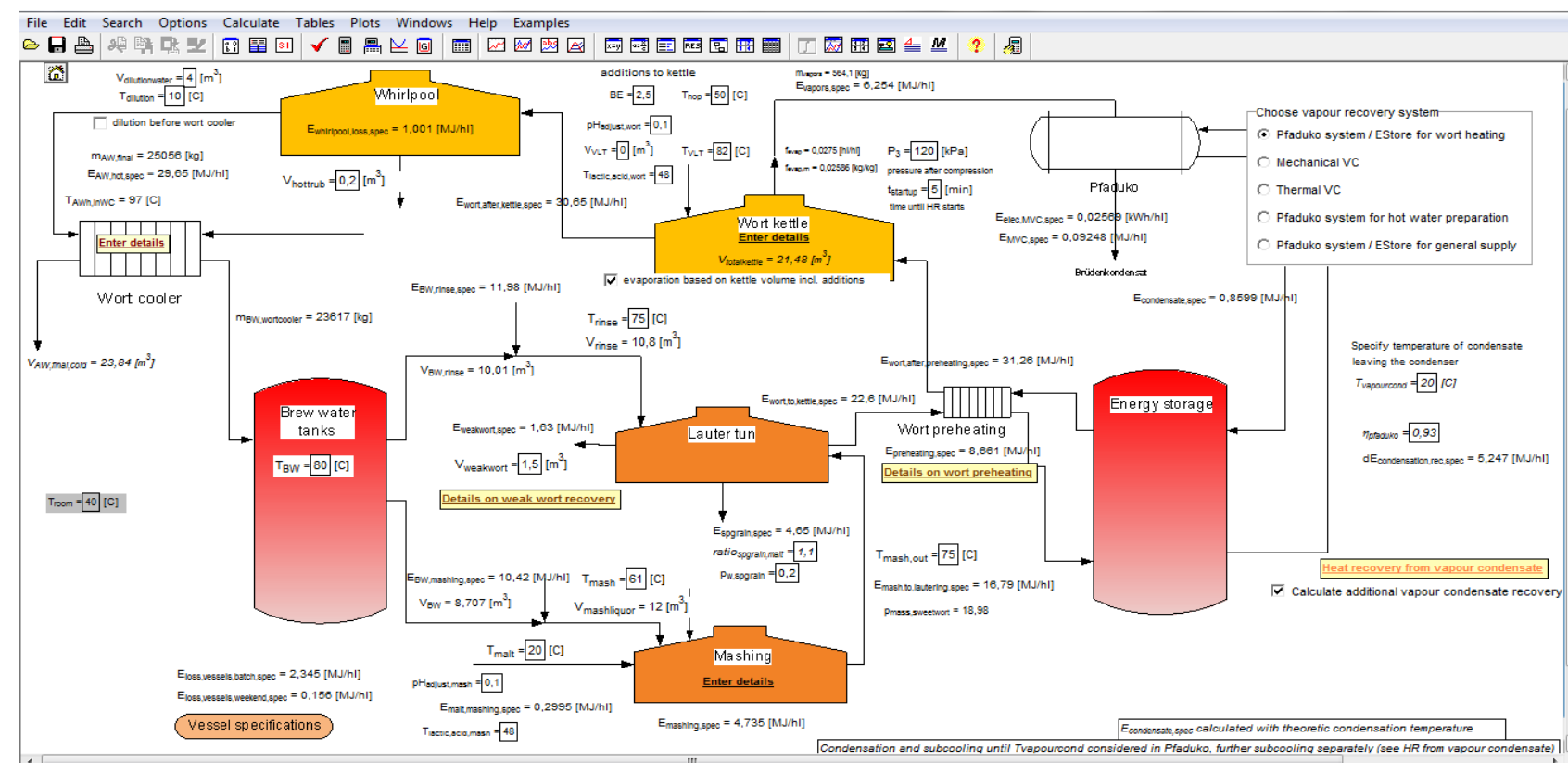
2011

2017

2026

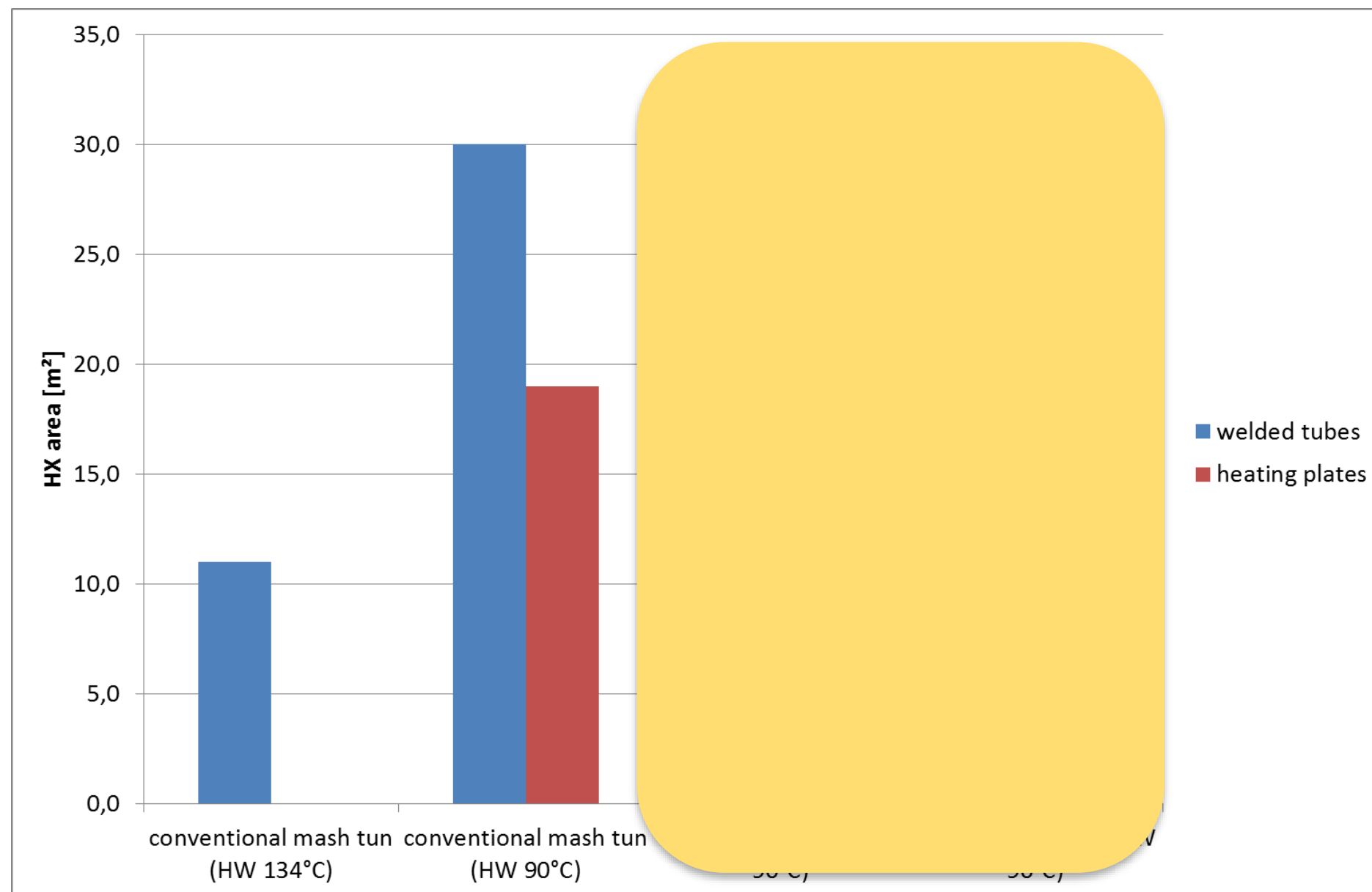
# Energy supply in industry heavily relies on process technologies

## Work performed with Brewery Göss, Austria 2008 - 2016

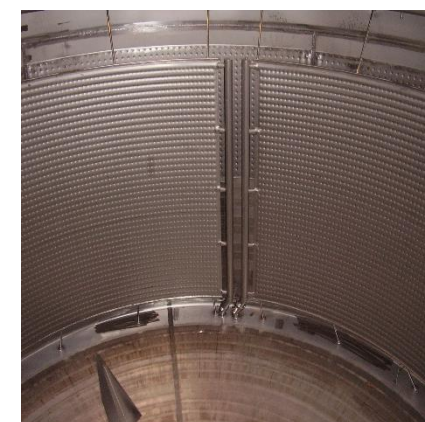


# Energy supply design is dictated by process technologies

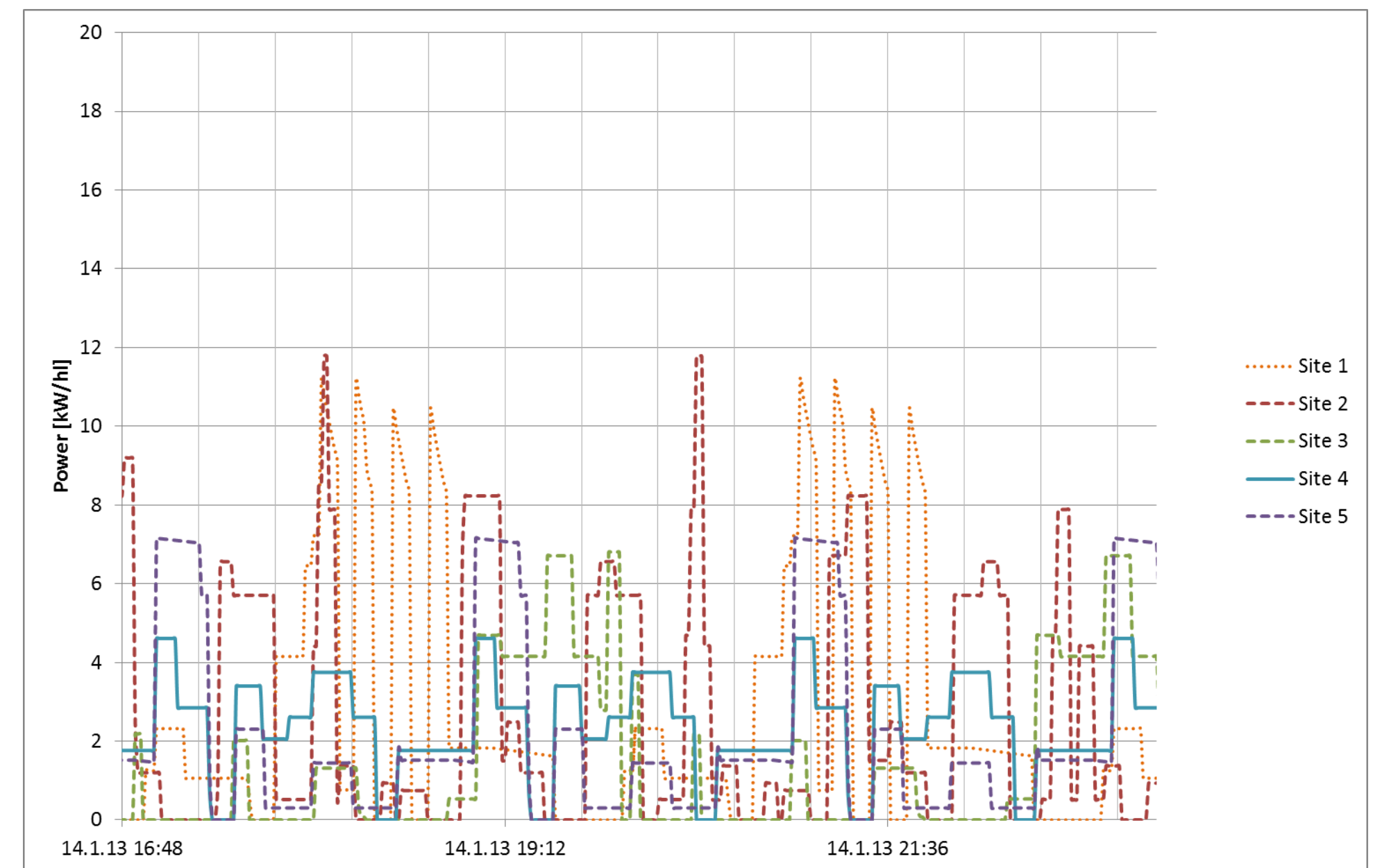
Retrofitting existing mash tun (400hl) with additional heating plates to allow for low temperature energy supply



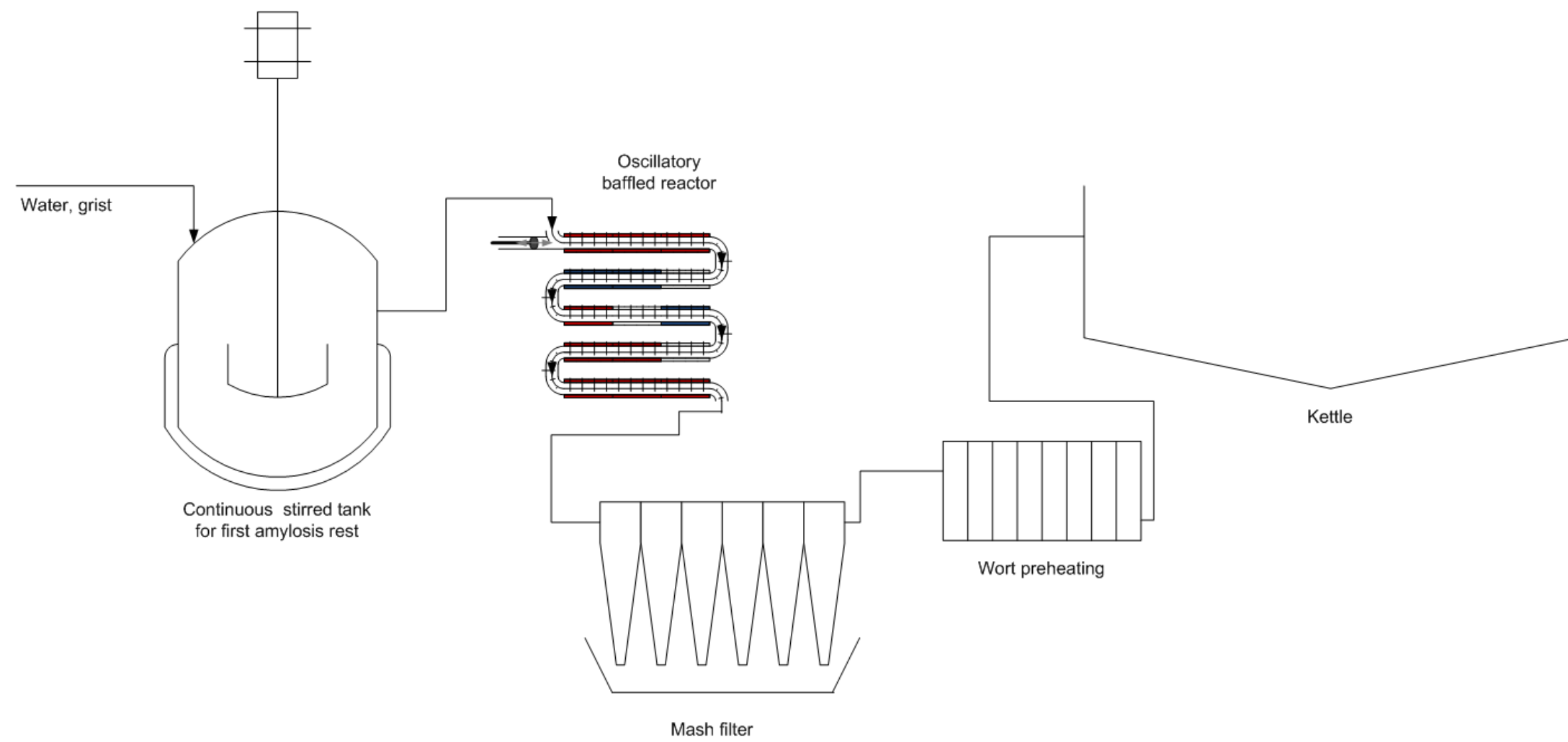
Brunner et al., 2013



GEA Brewery Systems



# Continuous reactor debottlenecking renewable energy supply



Power density calculation acc. to Baird and Stonestreet

Quasi-steady model for  $St < 0.2$ , recommended for low frequencies and high amplitudes; eddy enhancement model for  $St > 0.2$

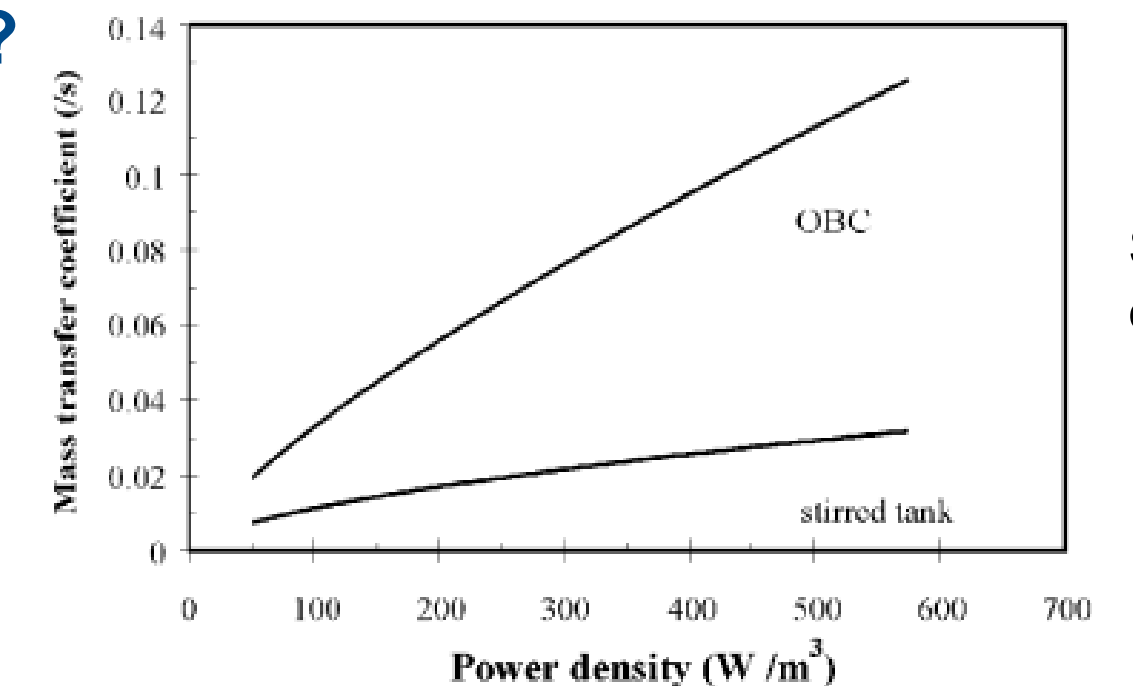
$St \sim \text{diameter} / \text{oscillation amplitude}$

$$\varepsilon_v = \frac{2n\rho}{3\pi L_p C_0^2} \left( \frac{1}{S^2} - 1 \right) (\omega x_0)^3$$

Table 6-14: OBR design for 200 hl/h production

$\nu$	$d$	$u$	$z$	$Q$	$Re_o$	$Re_{net}$	velocity ratio	$x$	Strouhal number	number of baffles	total power density
$\mu$	$m$	$m/s$	$m$	$hl/h$	$\mu$	$\mu$	$\mu$	$\mu$	$\mu$	$\mu$	$W/m^3$
$\nu = 130 \text{ mPas}, \text{ residence time} = 30 \text{ min}$											
Design-6	0.33	0.06	116.9	200	1391	180	7.7	0.04	0.66	236	829
Design-7	0.33	0.06	116.9	200	2782	180	15.5	0.08	0.33	236	3169
$\nu = 20 \text{ mPas}, \text{ residence time} = 30 \text{ min}$											
Design-6	0.33	0.06	116.9	200	9040	1168	7.7	0.04	0.66	236	829
Design-7	0.33	0.06	116.9	200	18080	1168	15.5	0.08	0.33	236	3169

Can we reduce Wh/kg production via much higher process efficiency?



Stonestreet et al, 2002

# Proven processability of thick slurries and high conversion efficiencies in cellulose hydrolysis

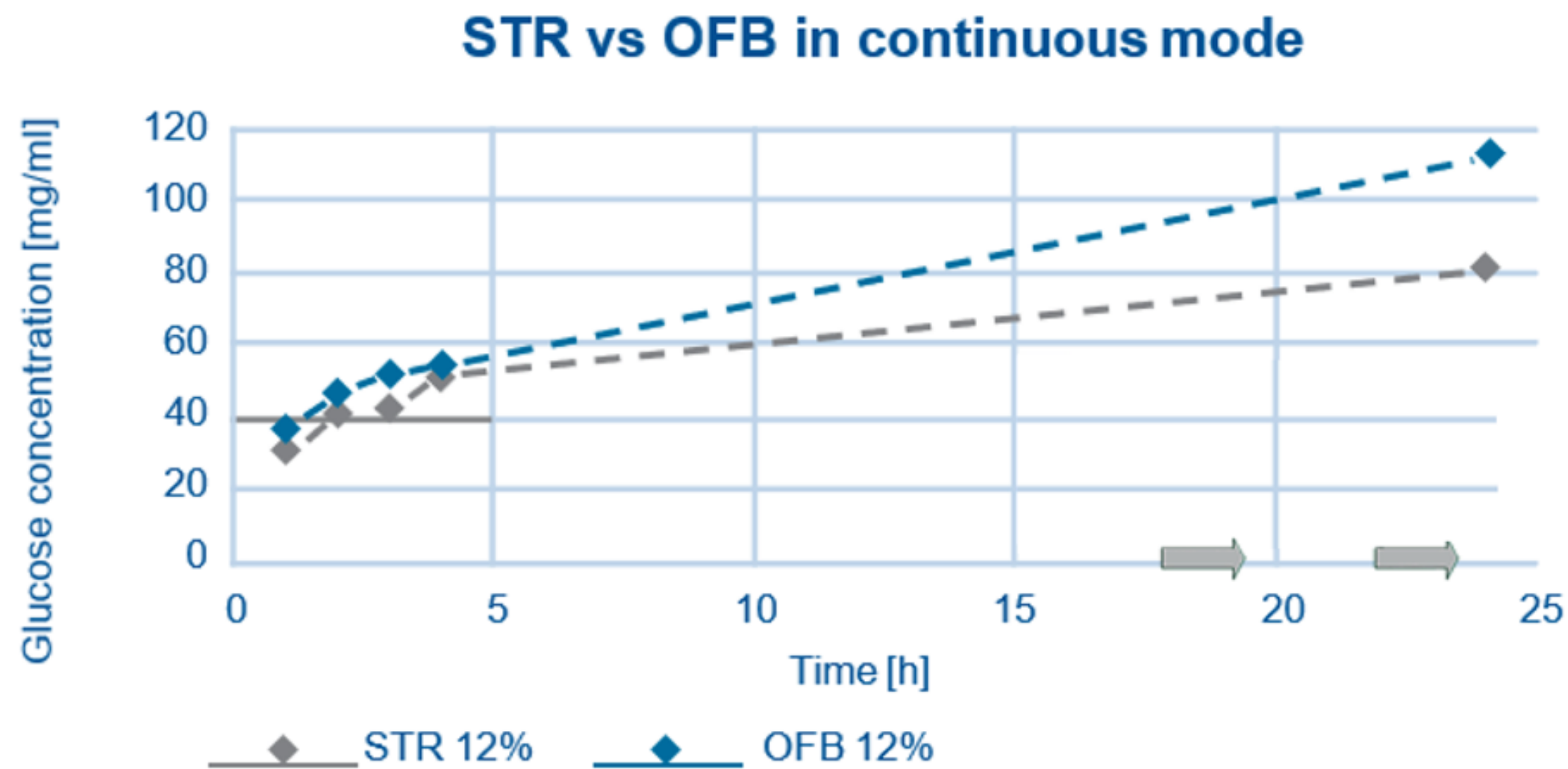


Figure 2: Sugar concentration of 12% cellulose solid loading in continuous OFB compared to STR set-up. (Exp. Cond.:  $\alpha$ -cellulose in 50 mM sodium citrate buffer, pH 4.8, at 50 °C, 10.3 FPU enzyme, 3.55 Hz frequency, 10 mm amplitude)

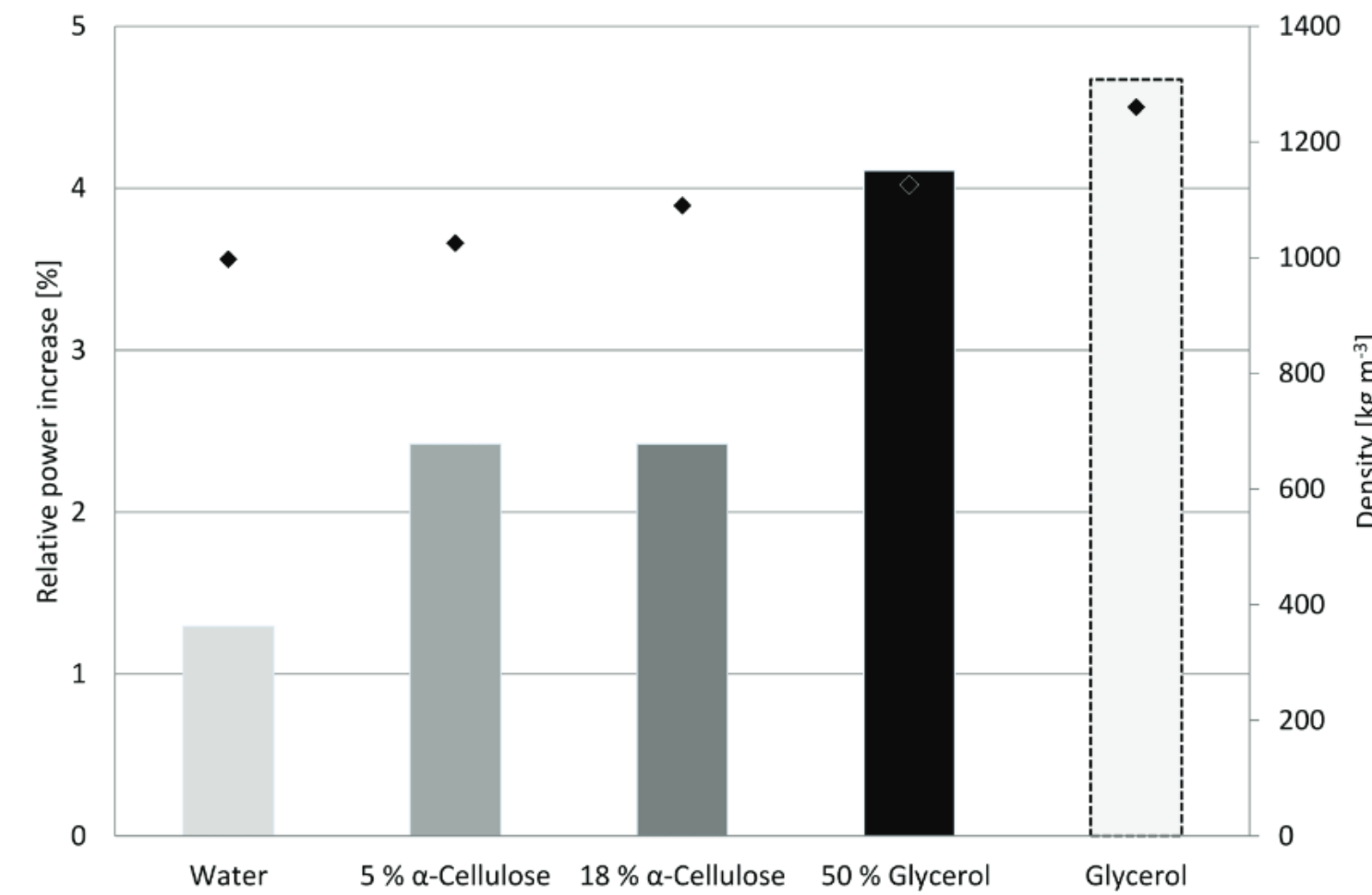


Fig. 2 – Influence of different densities on the energy input in the OFB shown as relative power increase (3 mm baffle, 6 mm amplitude)

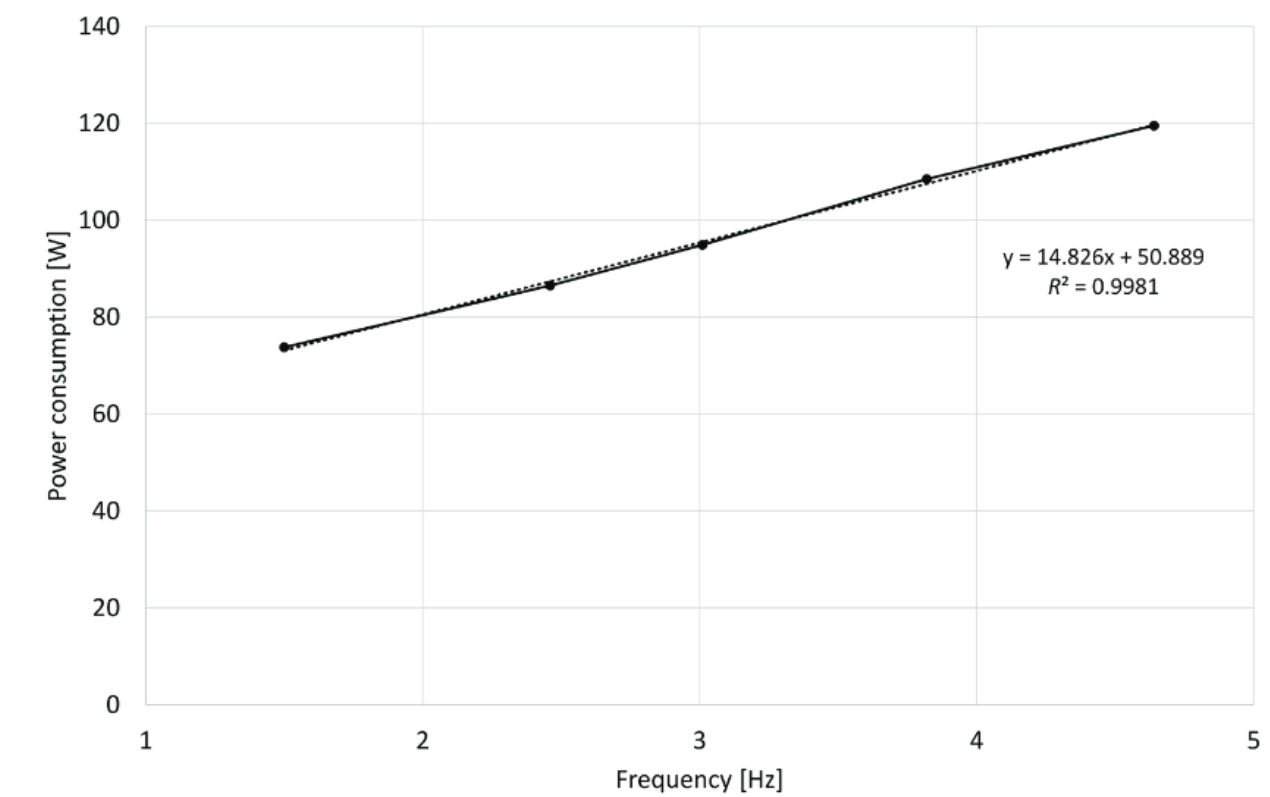


Fig. 3 – Oscillatory power consumption as a function of different frequencies (12 % SL,  $\alpha$ -cellulose, 3 mm baffle, 10 mm amplitude)

% SL	STR system			OFB system			
	Stirring speed [rpm]	Power density [W m <sup>-2</sup> ]	Sugar formation [g L <sup>-1</sup> ]	Frequency [Hz]	Power density [W m <sup>-2</sup> ]	Sugar formation [g L <sup>-1</sup> ]	Other parameter
12 % SL	60	1.43	65.54	1.5	19.45	69.19	3 mm B.
	120	11.46	66.73				
	250	103.64	66.29				
15 % SL	500	1042.23	77	2.05	24.9	78.78	2 mm B.
				2.05	49.93	82.16	3 mm B.
				2.05	49.93	77.3	3 mm B./ 8 FPU g <sup>-1</sup>

Buchmaier et al, 2020; Muster-Slawitsch et al, 2022; Griesbacher, 2022 Master Thesis at AEE INTEC

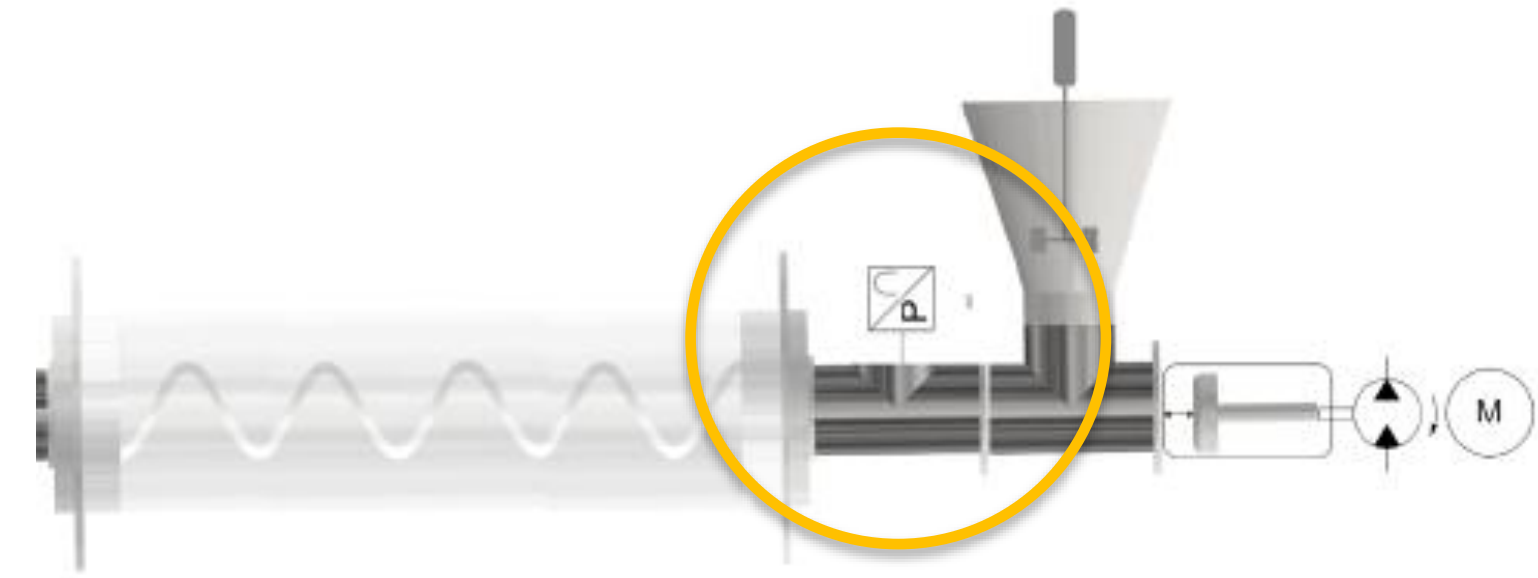
# OFB Power Measurement

→ “minimal energy input for oscillatory mixing”

## → measurement:

Power calculated based on a pressure indicator (membrane)

Data generated → P different feedstocks at various solid loadings

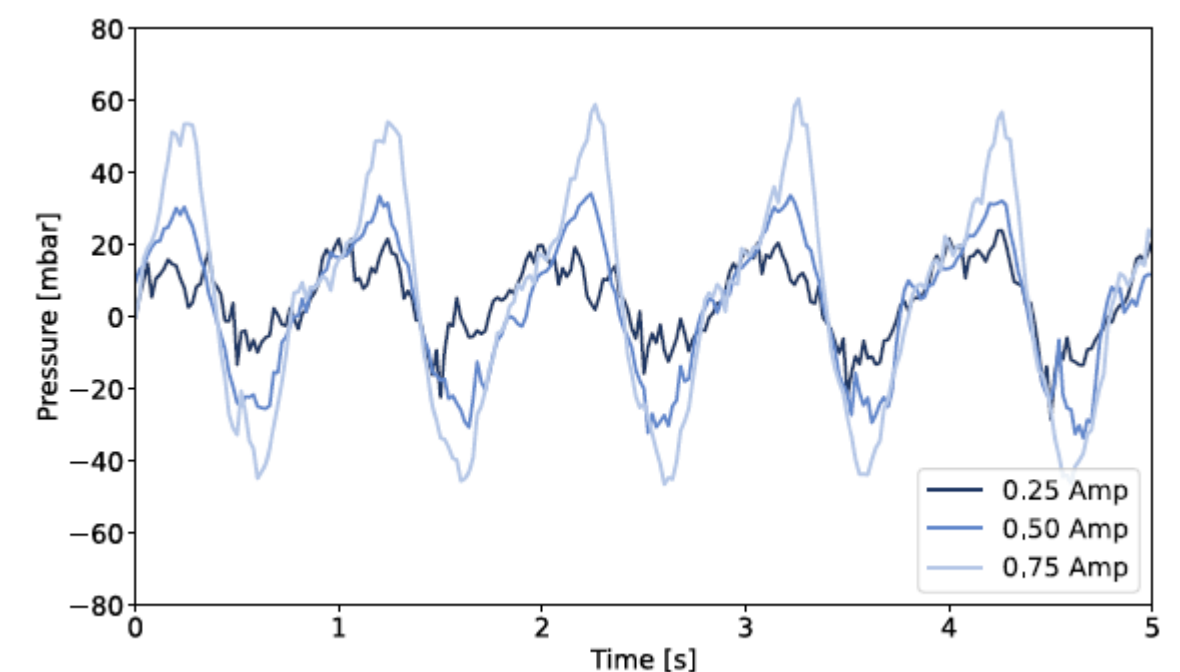


**Background Calculation:** The minimal power required to oscillate the slurry,  $P$  [W], is determined by the product of pressure [Pa], cross-sectional area [A,  $m^2$ ], and velocity [ $v$ , m/s], dependent on position angle, maximum displacement ( $x_0$ , m), frequency ( $f$ , 1/s), and  $\pi$

$$P [W] = \text{pressure [Pa]} * A [m^2] * v \left[ \frac{m}{s} \right] \quad (6)$$

$$v \left[ \frac{m}{s} \right] = \cos(\text{Position angle}) * 2 * x_0 [m] * \pi * f \left[ \frac{1}{s} \right] \quad (7)$$

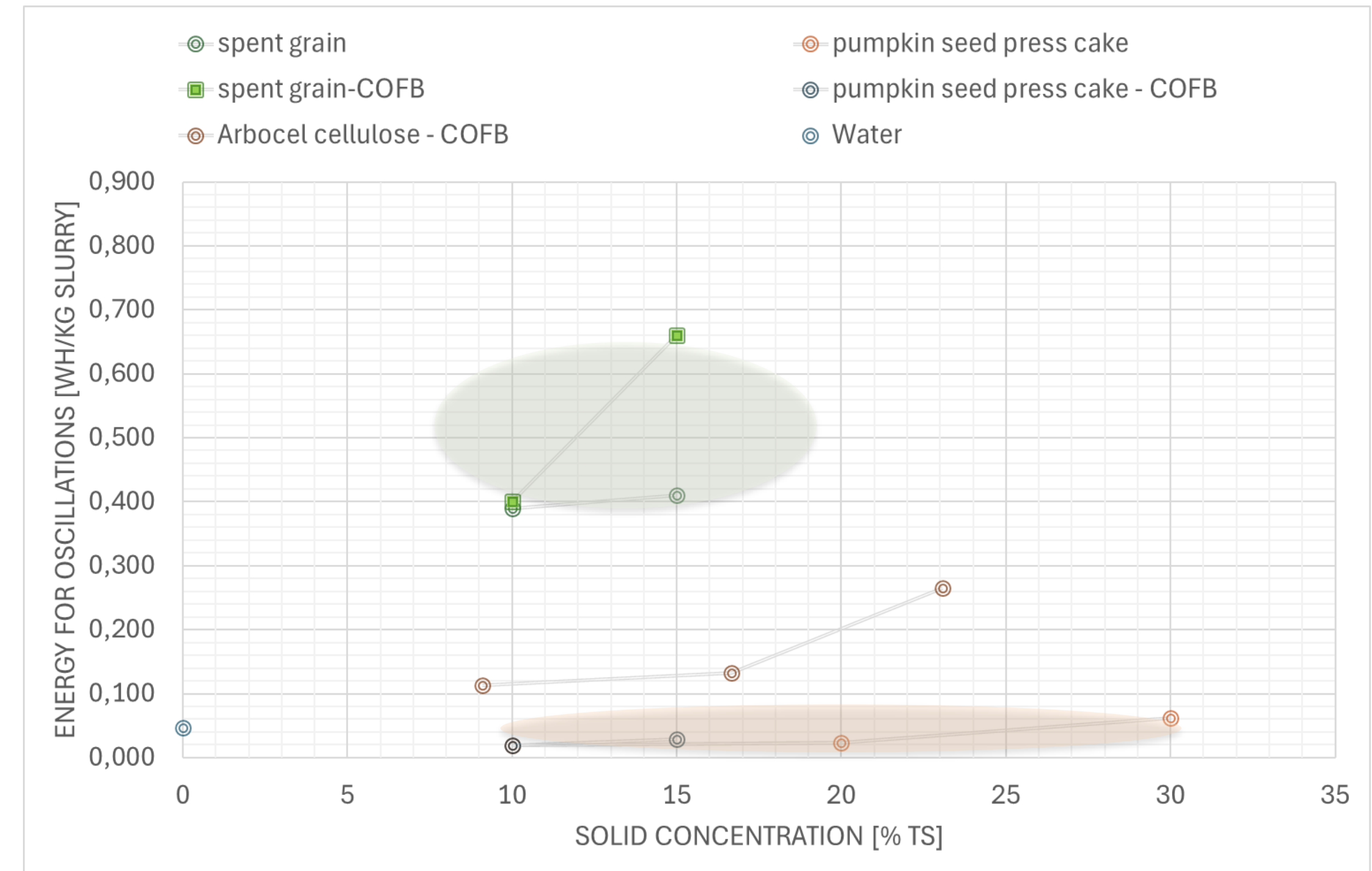
$$A [m^2] = D^2 [m] * \frac{\pi}{4} \quad (8)$$



Adriaenssens et.al, Chemical Engineering Science 234, 2026

# Energy for oscillations for slurry processing

## Batch processing and continuous processing give very similar values

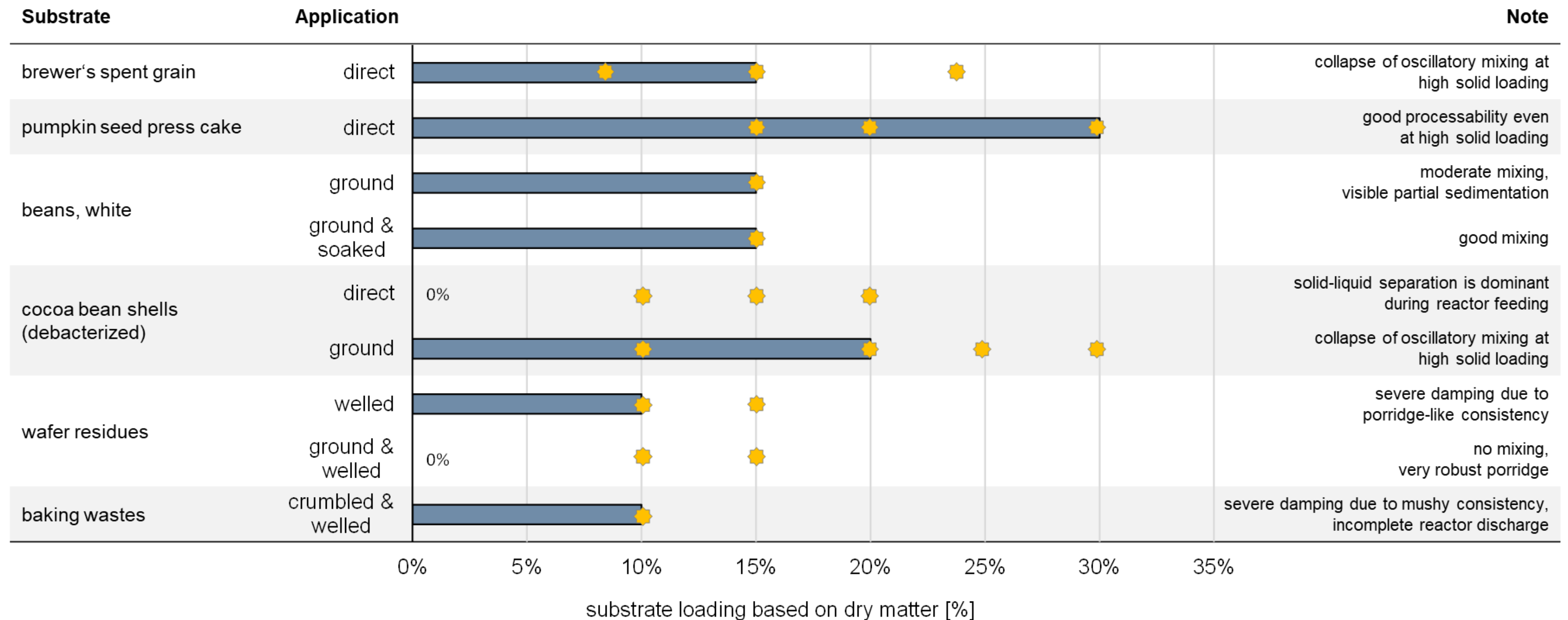


# Operating boundaries for good mixing

## Substrate Processability: Maximum Solid Loadings in the OFR

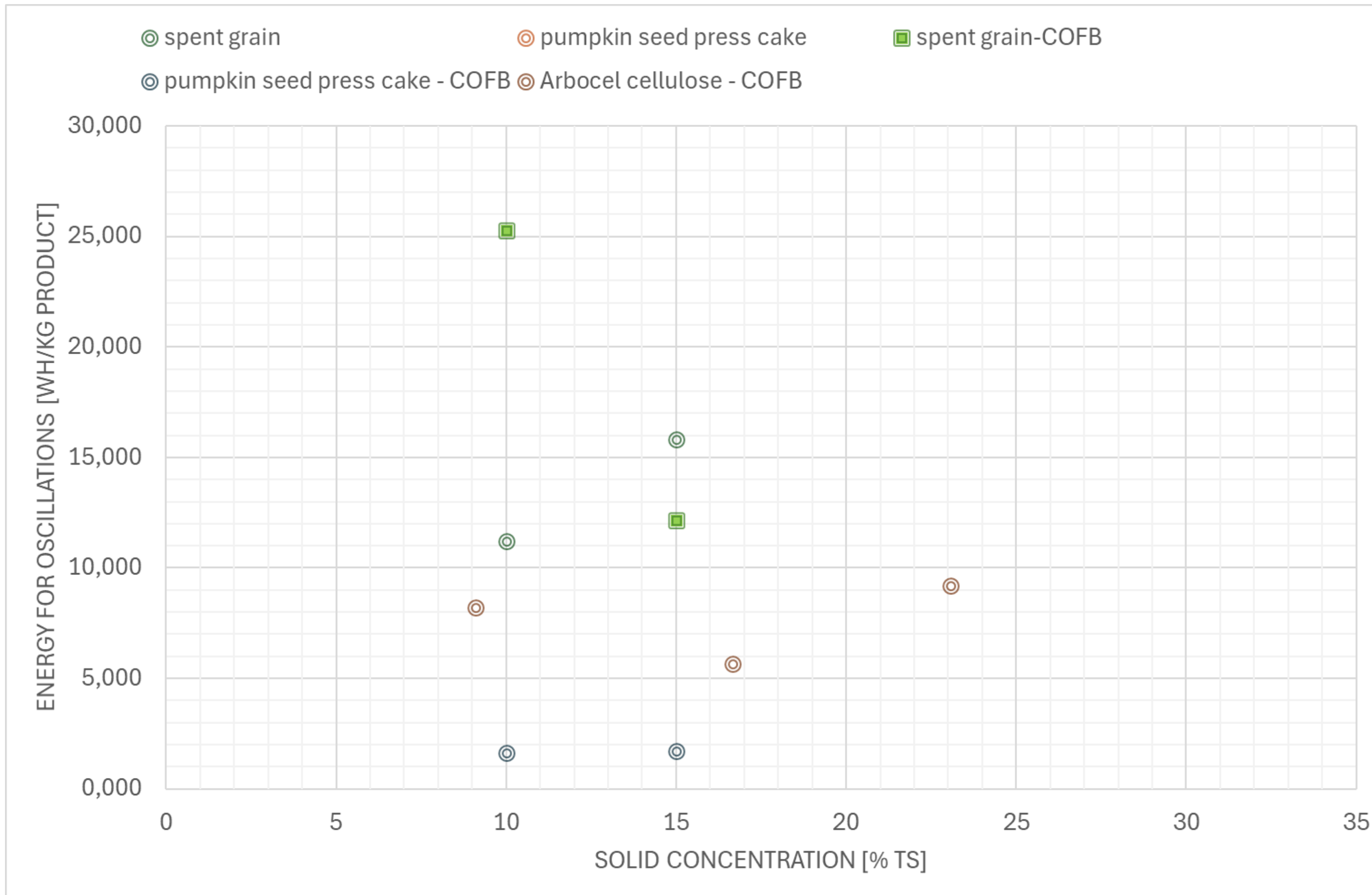
09/01/2025

... confirmed, operationally feasible operating window
  ... conducted test trials



Swelling: 30 min, unstirred, room temperature, aqueous 0.2 M NaCl solution // Soaking: 18 h, unstirred, room temperature, aqueous 0.2 M NaCl solution

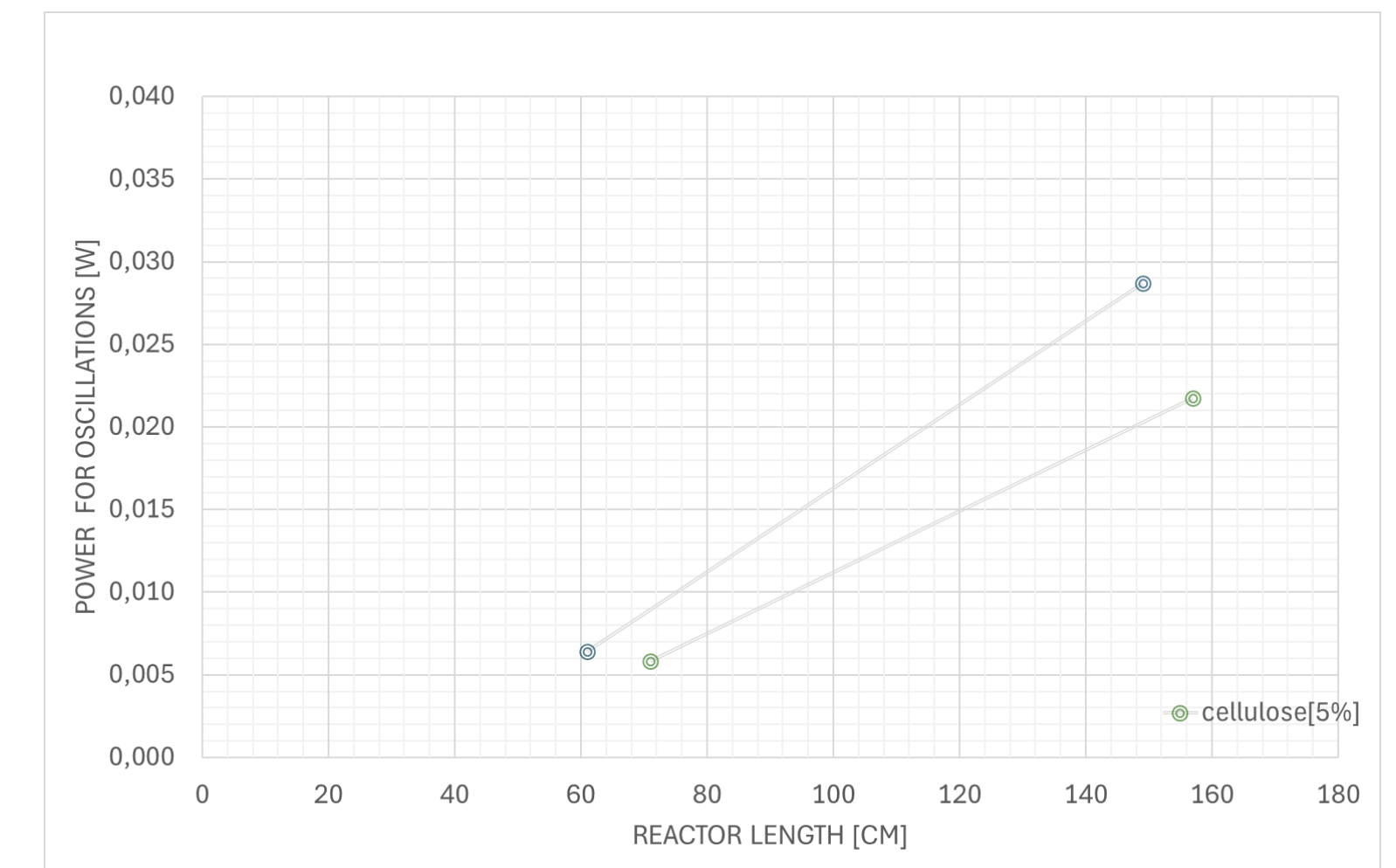
# Energy for oscillations per gained product



Promising energy efficiency kg product/Wh

→ Challenge in scaling

→ diameter and length



# Continuous In-Line Product separation in enzymatic hydrolysis of cellulose

In-line product separation in a continuous oscillatory flow bioreactor as process intensification and product inhibition mitigation strategy

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<sup>a</sup> AEE - Institute for Sustainable Technologies A-8200 Gleisdorf, Feldgasse 19, Austria

<sup>b</sup> Wood K plus - Competence Center for Wood Composites & Wood Chemistry, Kompetenzzentrum Holz GmbH, Altenbergerstraße 69 A 4040 Linz, Austria

model substrate: Arbocel®  
 UFC 100  
 Enzyme: ViscoPract® CX  
 Buffer: 50 mM sodium citrate buffer  
 T: 50°C  
 τ: 3h

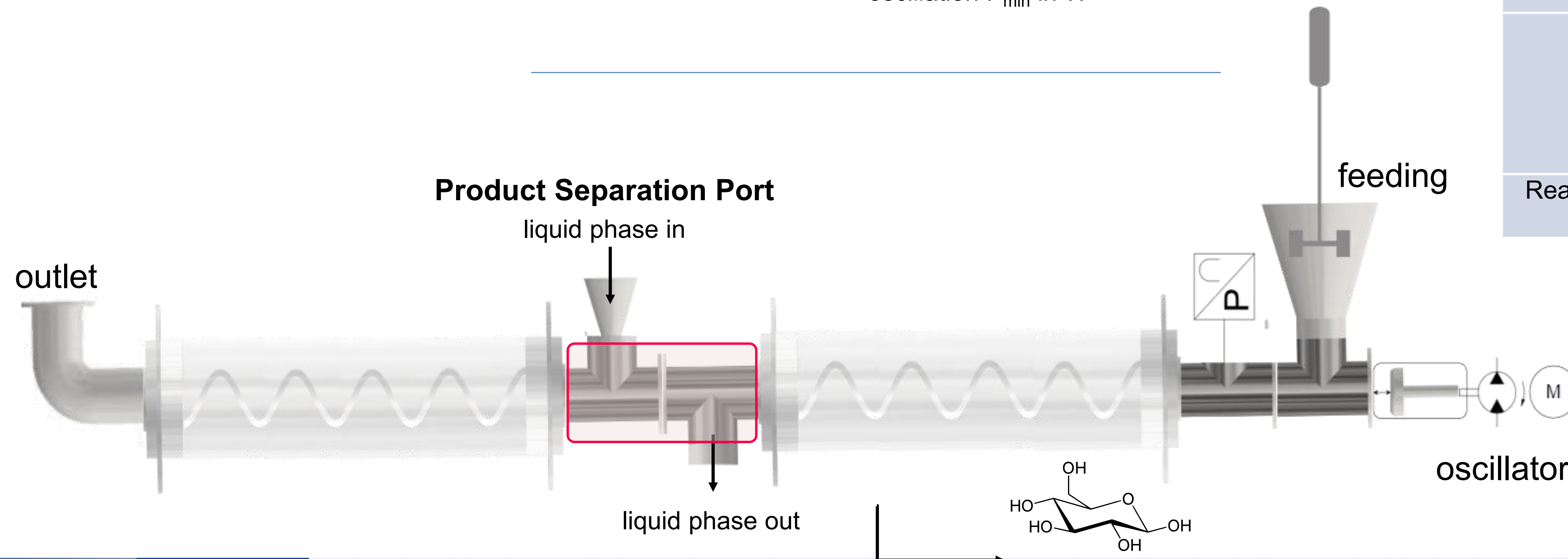
## Factors:

Solid Loading (SL):  
 9% - 17% - 23% SL  
 Separation Rate:  
 0– 50 – 90 mL<sub>Buffer</sub>/h  
 Enzyme to Substrate Ratio  
 (E/S Ratio):  
 1% - 3% - 5% E/S

## Responses:

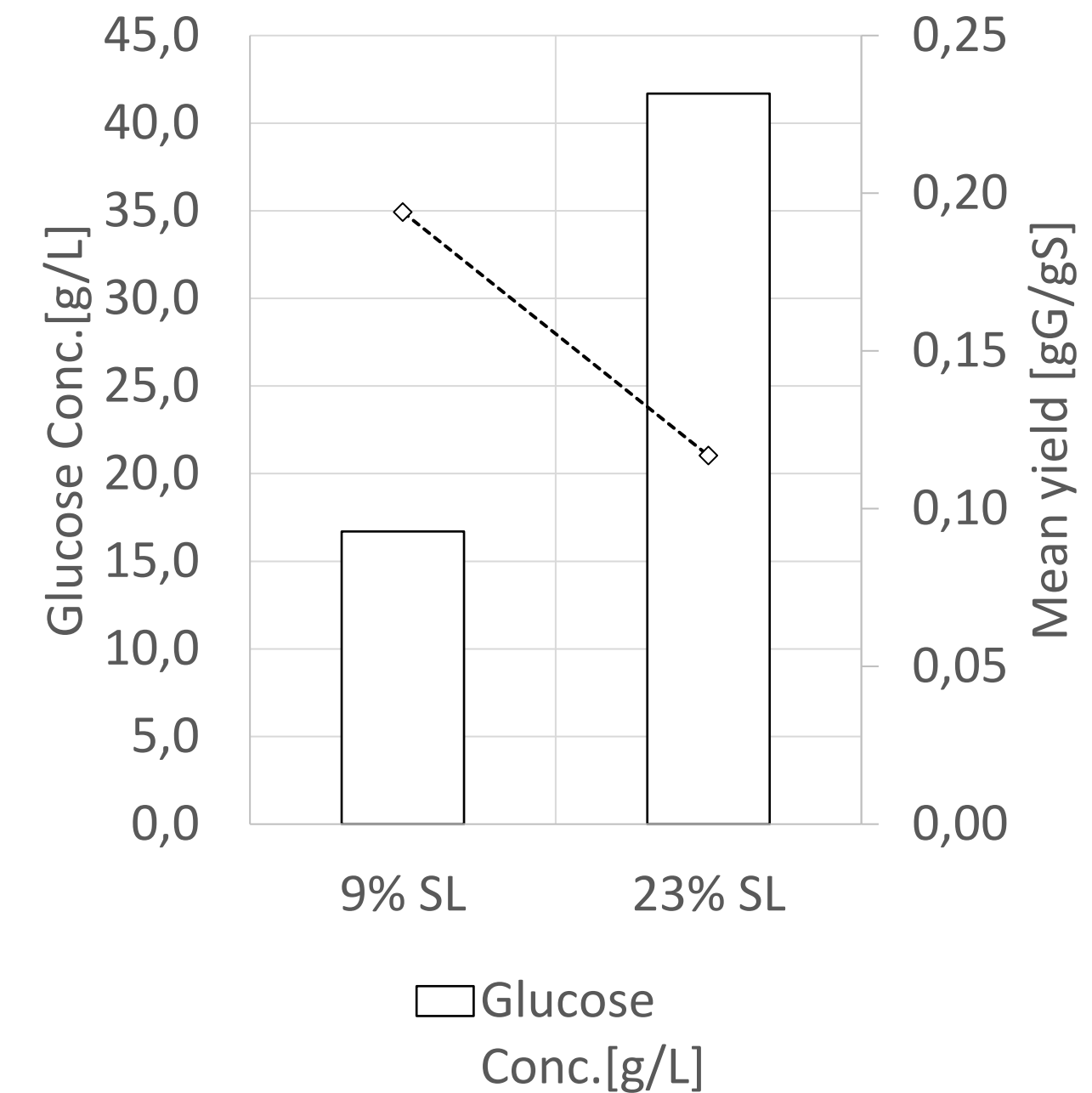
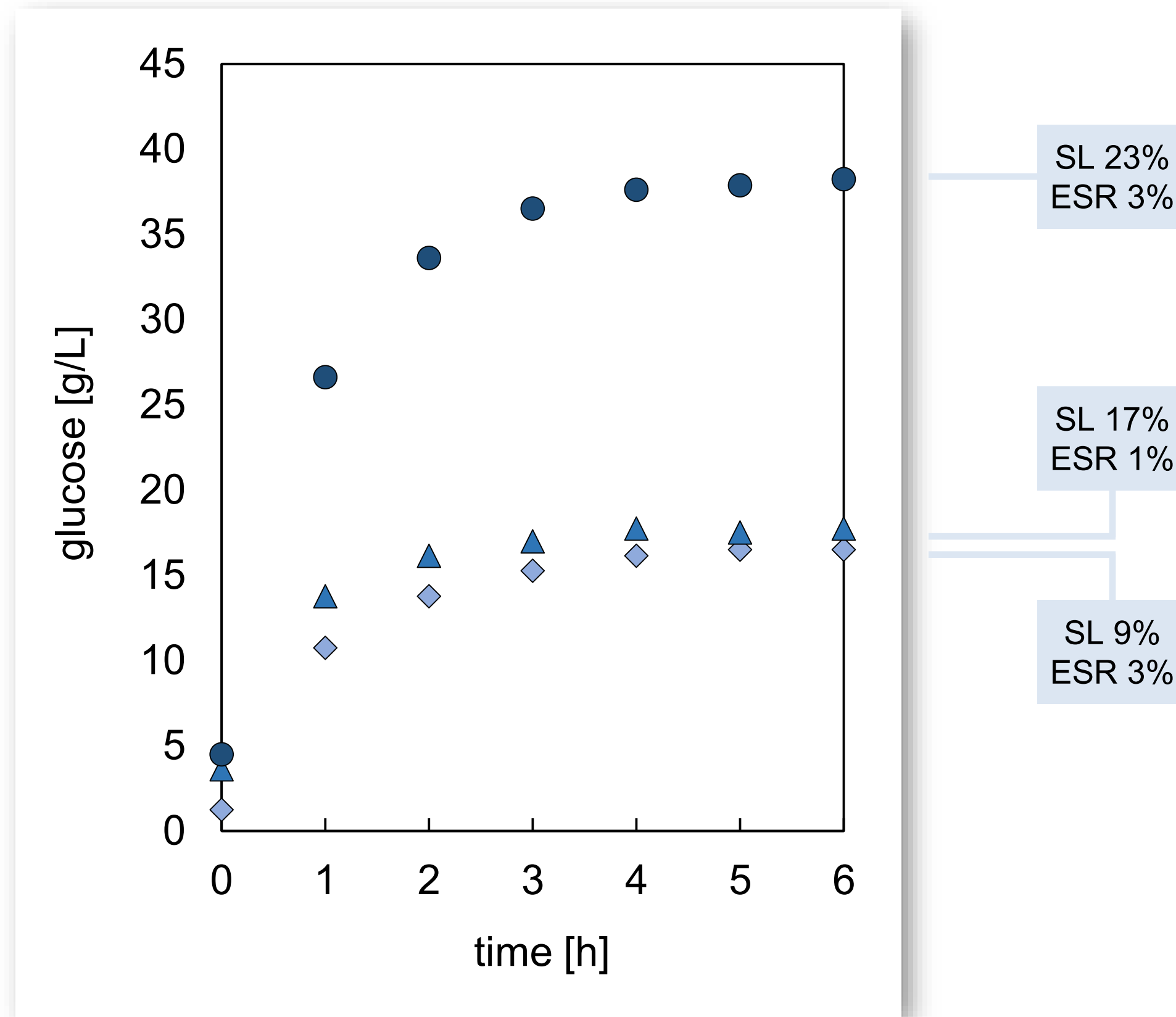
Glucose Concentration C in g/L  
 Glucose Yield Y in gG/gS  
 Enzymatic Productivity E in g<sub>Glucose</sub>/g<sub>Enzyme</sub>  
 Minimum required power for oscillation P<sub>min</sub> in W

Center to peak amplitude $x_0$	10 mm
Frequency f	1.5 Hz
Inner tube diameter d	25 mm
Wall thickness	5 mm
Baffle type	Helical, 3 mm thickness, pitch = 37.5 mm
Reaction temperature (T)	50 ± 1.5 °C



# Glucose Concentration and yield (no product separation)

Buchmaier et al., Cleaner Chemical Engineering 11 (2025)



high substrate loadings obviously lead to high concentrations, however lower specific yield

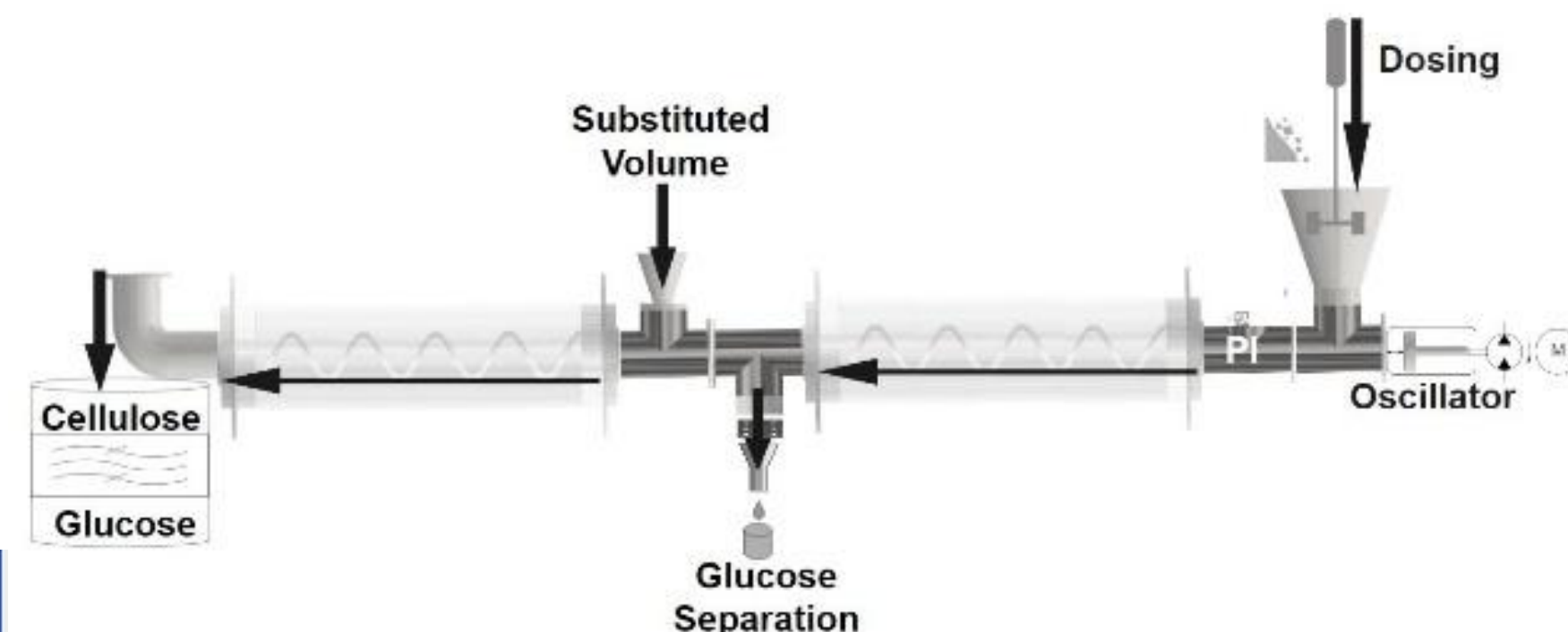
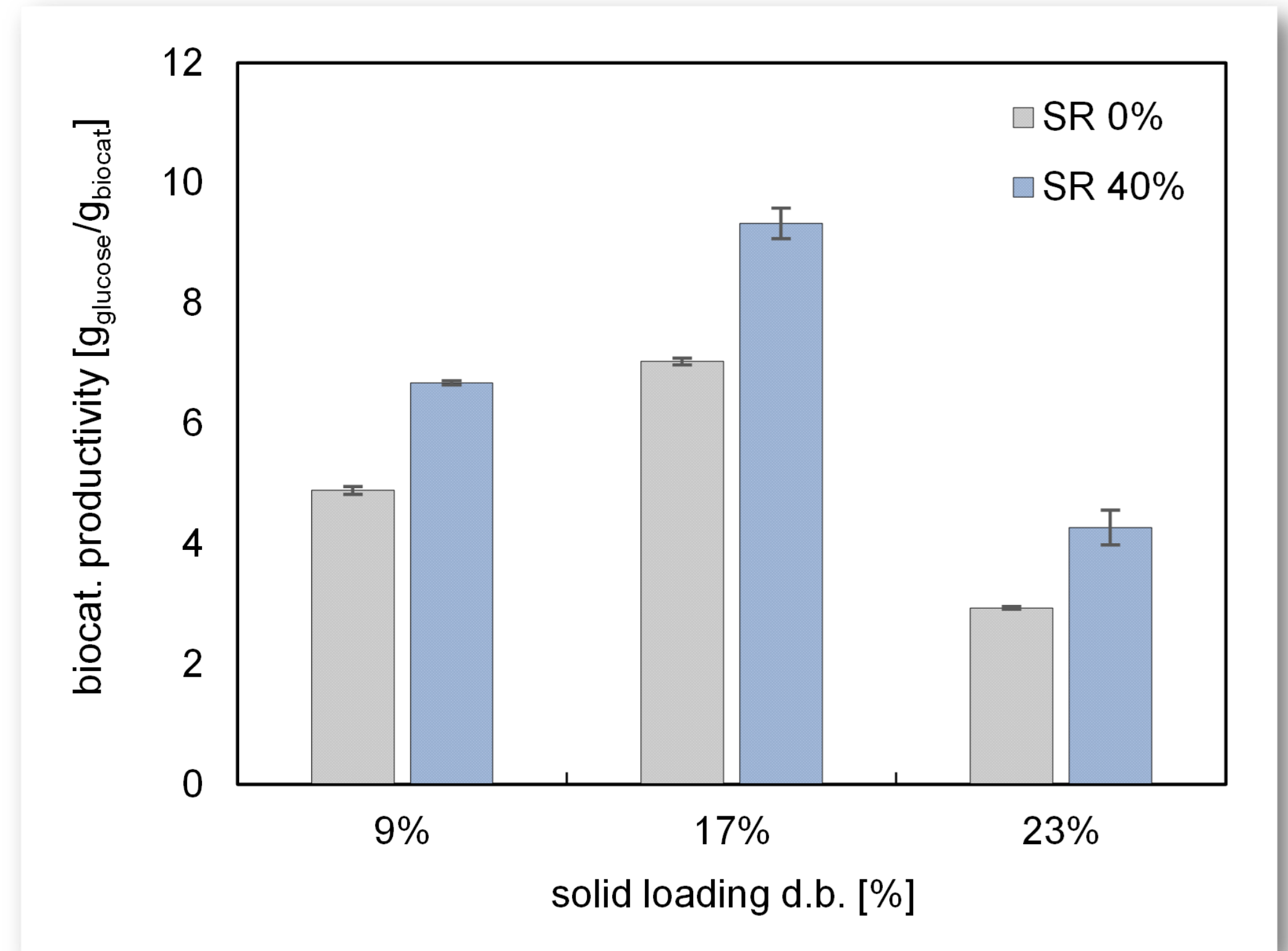
stable steady-state operations after 1  $\tau$  (3 h)

constant conditions: Na-citrate buffer (20 mM, pH 5.25), biocatalyst mix A, 50 °C, residence time 3 h, flow rate 228 mL/h, continuous operations (COFB),  $x_0$  10 mm (ctp), 1.5 Hz, model substrate A

# Glucose Yield with in-situ product separation

Buchmaier et al., Cleaner Chemical Engineering 11 (2025)

- in-situ product outtake well possible in OFR
- Applying in-situ product separation enhances yield significantly by ~ 40%**
- Energy demand for oscillation (based on pressure sensor) resulted **8.2-9.2 Wh/kg glucose** respectively **>100 kg glucose/kWh**
- STR, Correa et al, 2026: **0,3-0,4 kg/kWh in STR** (measured by torque force) *Proving Abbot et al, 2014, calculating significant reduction in enzymatic saccherification energy vs. STRs*



	9% SL	17% SL	23% SL
$Re_0 (-)$	271	17	3
$Re_n (-)$	0.37	0.02	0.004
$\Psi (-)$	733		

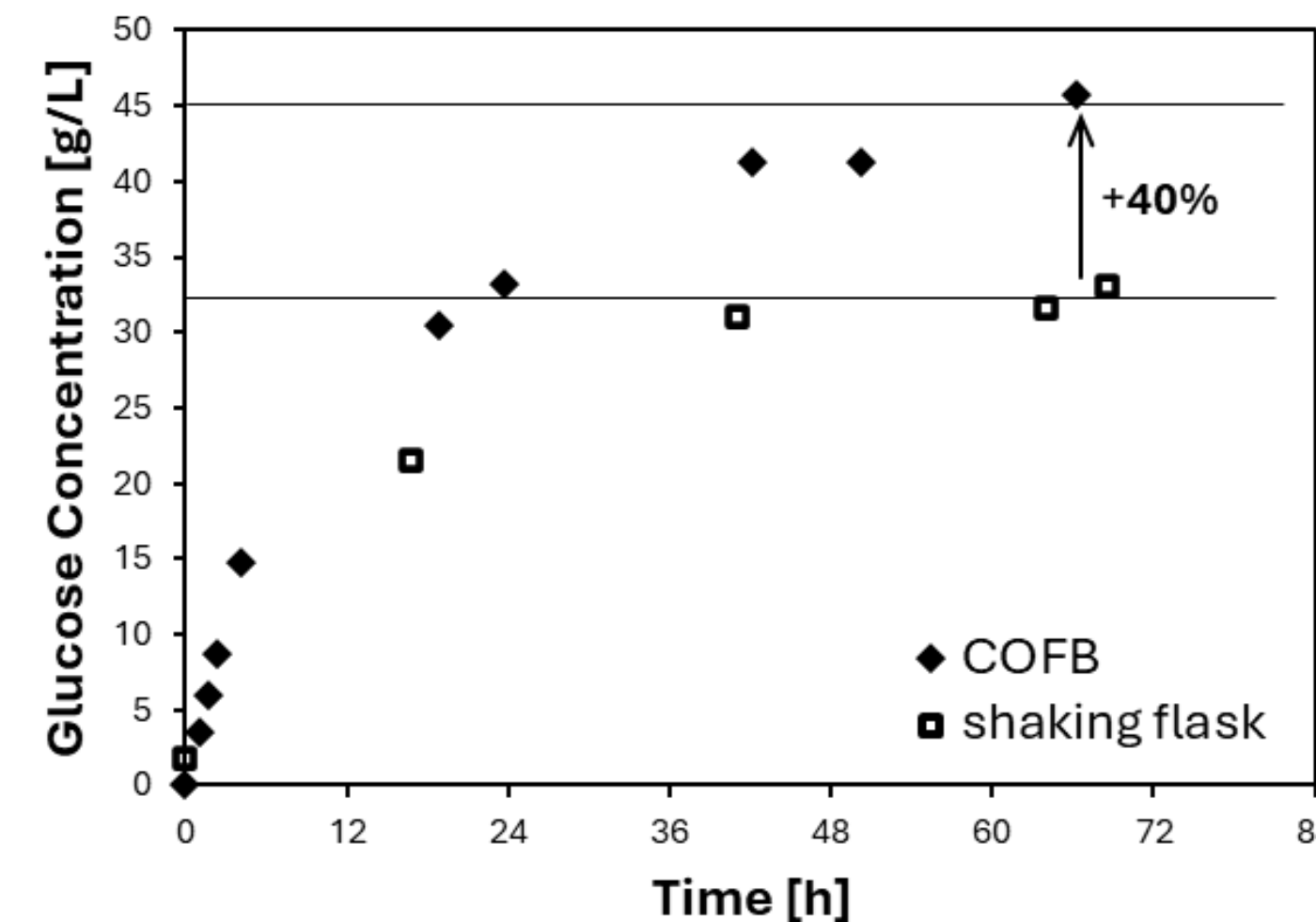
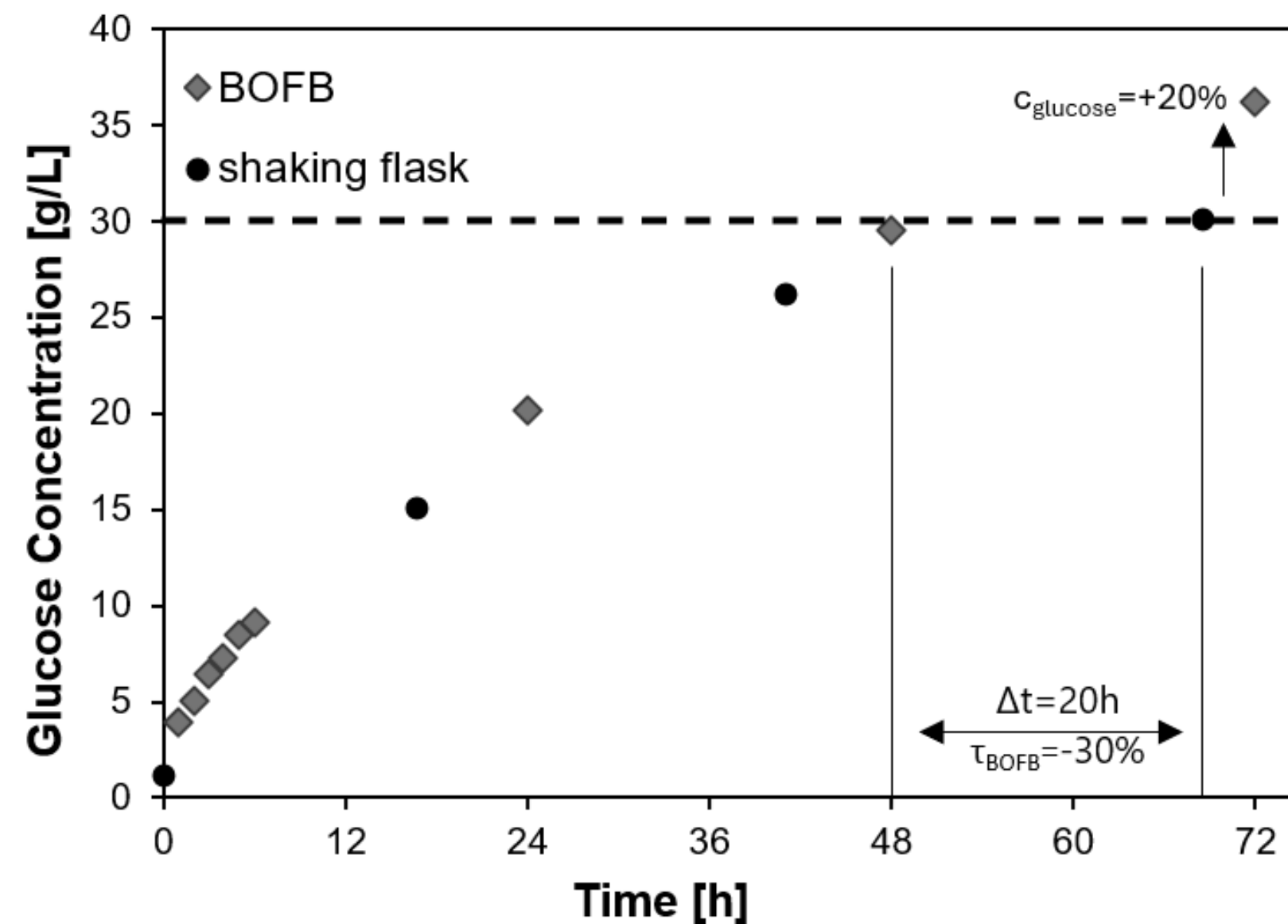
# Shaked flasks – BOFB – COFB comparison with lignocellulosic substrate

Buchmaier et al., Cleaner Chemical Engineering 11 (2025)

Specifications lignocellulose  
 Dry content: 25.39% (w/w)  
 Glucan content\*: 51.13% (w/w)  
 Xylan content\*: 4.56% (w/w)  
 Enzyme Blend: ViscoPract® CX

Experimental conditions:  
 Temperature: 50°C  
 Buffer: 50 mM Na-Citrate, pH 5.25  
 Density: 1.005 g/cm<sup>3</sup>  
 Enzyme-to-substrate ratio: 5% (w/w) of DM  
 BOFB setup: l= 1.05m, vertical  
 COFB setup: l= 0.71m

\* Based on total hydrolysis

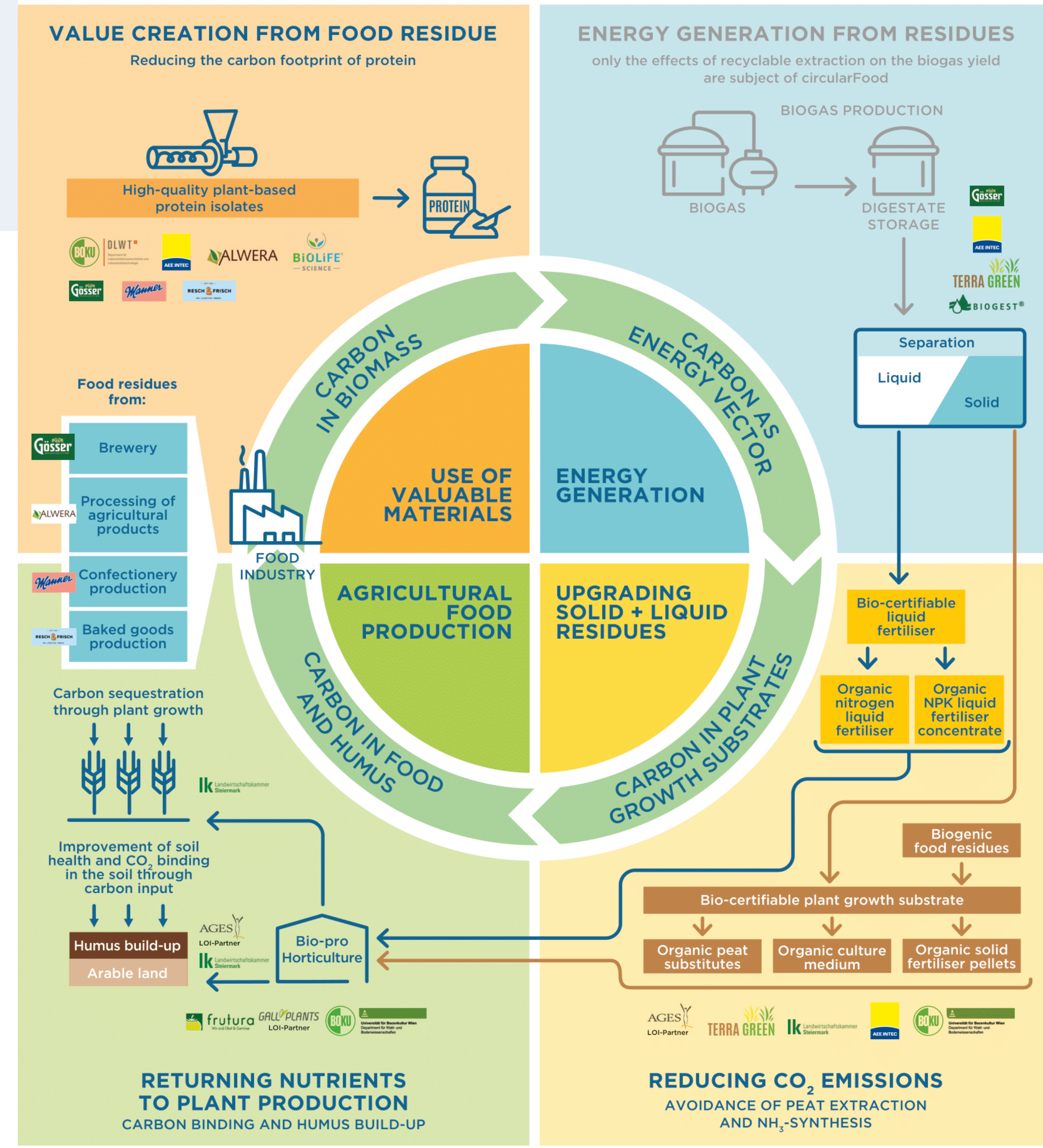


Decrease in residence time in continuous processing  
 1.7 x less time to reference concentration

## circularFood

### Innovation along the value chain

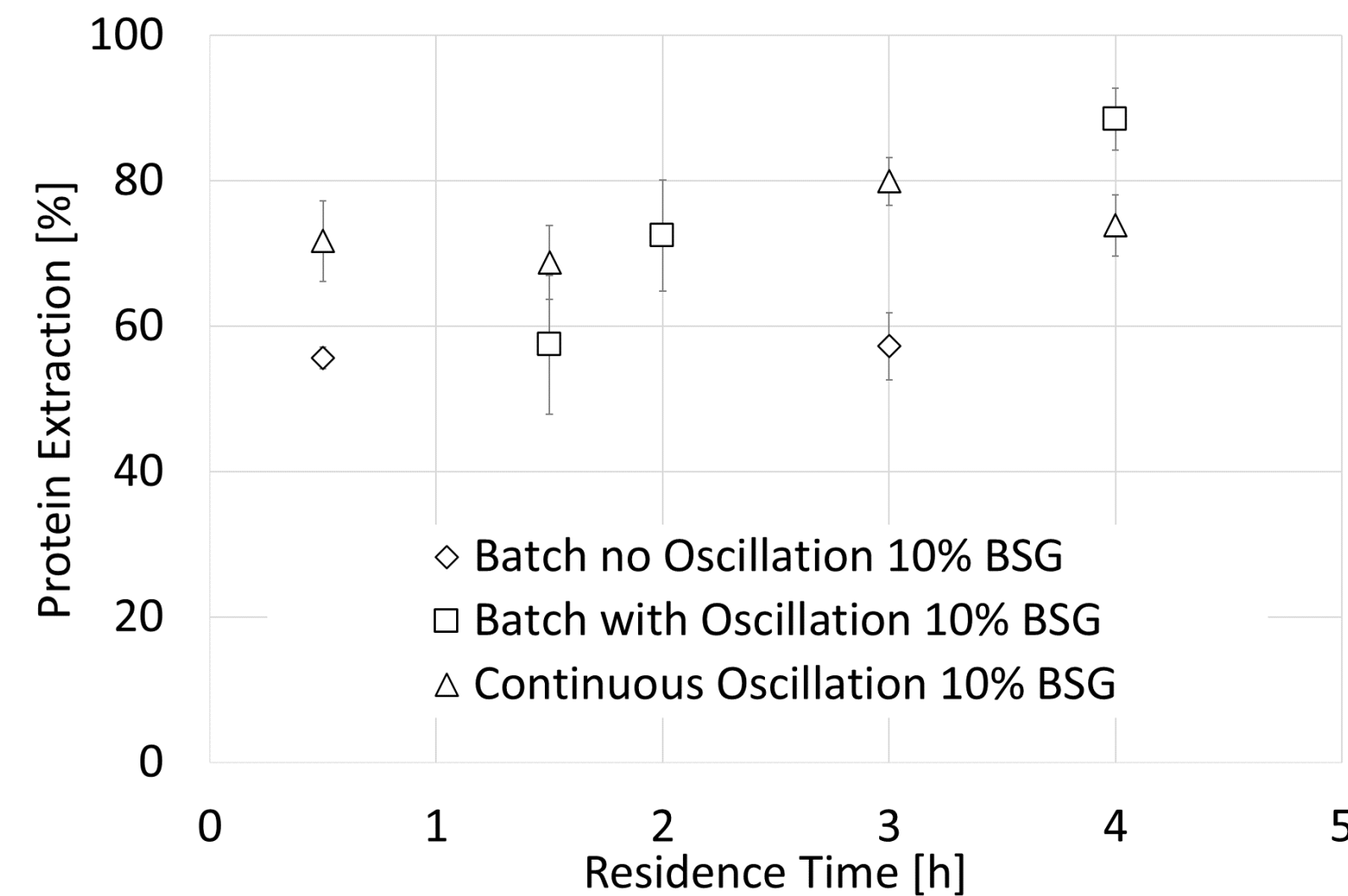
- New flow reactors for protein hydrolysis for sustainable **protein hydrolysates**
- Optimized **solid/liquid separation** of the fermentation residue
- **Bio-certifiable liquid fertilizer** through the use of membrane distillation
- New **peat substitutes**, organic growing media and organic solid fertilizer pellets through optimal blends
- **Plant tests and practical tests** in agriculture



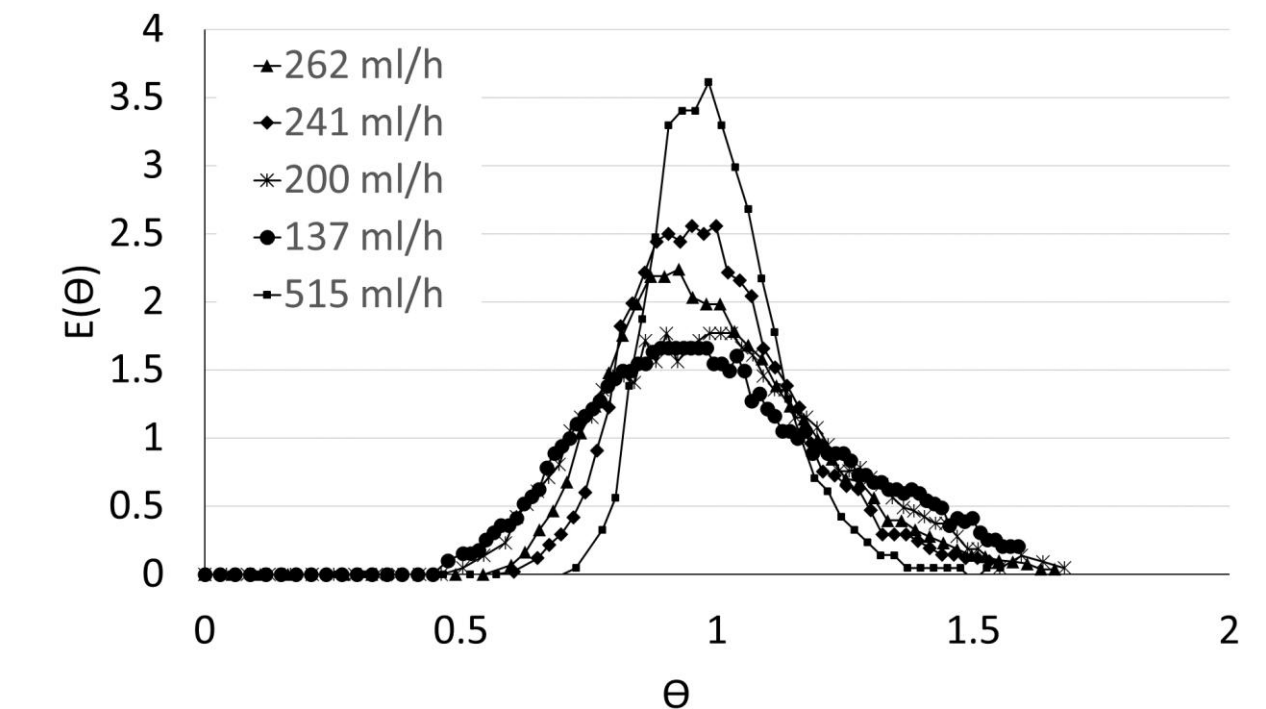
# Simple processing for effective hydrolysis

Buchmaier et al., Chemical Engineering & Processing: Process Intensification 200 (2024) 109772

- Flow behaviour analysis (**preliminary**)
  - Not ideal plug-flow behaviour
  - Very high velocity ratios
- Good processability of slurry without pre-treatment even in continuous set-up
- COFB proven as one-step extraction method for direct processing of residues in industry
  - 10–15% BSG substrate well processable
  - protein solubilization rates of 40% - 92% (average 65%, n = 31).
- **Vision: simple device, even if not full extraction of proteins**



Protein extraction in different reactor settings: without oscillation, BOFB and COFB. (BSG at 10 % solid loading in 200 mM sodium hydroxide (NaOH in dH<sub>2</sub>O), T = 50°C, f = 1.505 Hz, x<sub>0</sub> = 11 mm, l<sub>reactor</sub> = 0.89m)



The dimensionless RTD parameter, E(Θ), is plotted as a function of the normalized time Θ for different flow velocities.

Net Flow [ml/h]	Residence Time [h]	Reactor Length [m]	Velocity Ratio [-]	B <sub>0</sub> Number [-]
137	5.62	1.545	3644	38.4
200	3.97	1.545	2496	43.8
241	3.59	1.545	2071	83.8
262	3.06	1.545	1905	59.4
515	1.62	1.545	969	74.8
515	3.22	3.3	506	147.5

# Oscillatory flow enhancing membrane diffusion processes

**Direct contact membrane distillation:** thermal separation process

Driving force = partial vapour pressure

Large potential for industrial water recovery and ammonia recovery – tuning partial pressure difference can tune volatile recovery

$$C_m = \frac{J}{\Delta p}$$

J...Flux [kg/m<sup>2</sup>.h]  
 Δp...partial pressure difference  
 Cm...mass transfer coefficient

- New test-plant
- **Significant flux increase** under oscillatory flow conditions
  - Not necessarily highest Reynolds number, highest energy input leading to best results
  - Optimizing towards combined resource and energy efficiency

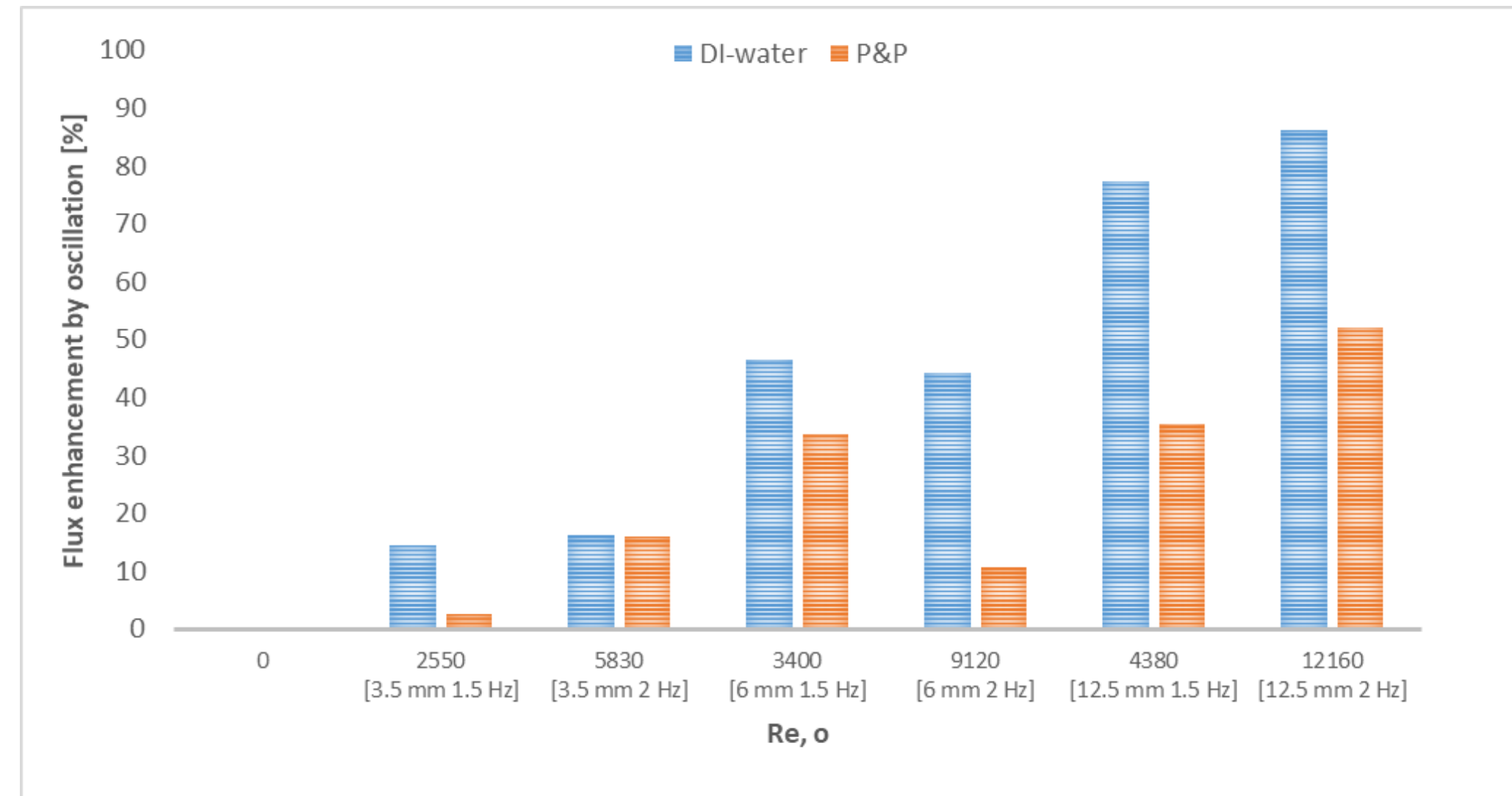
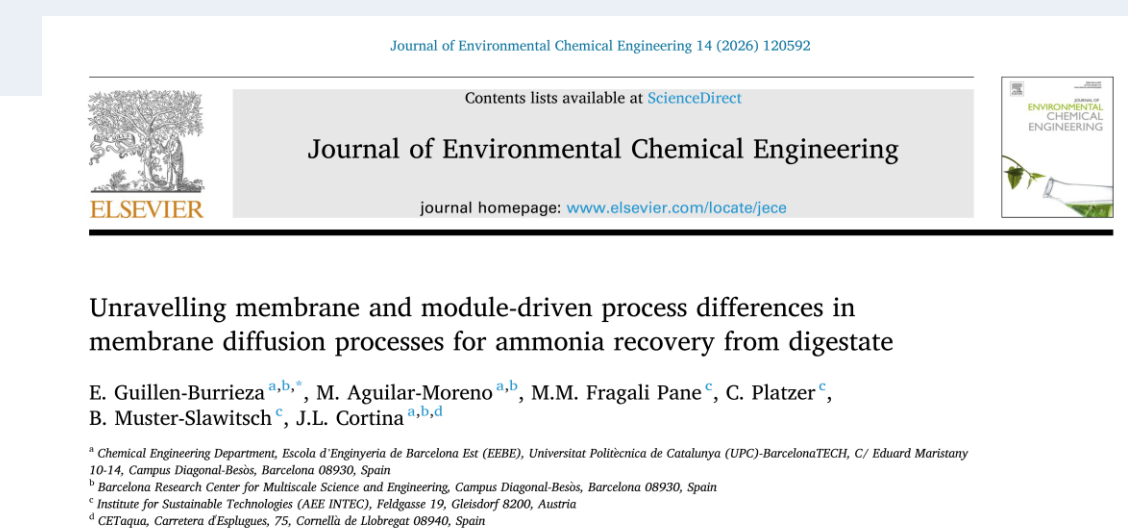


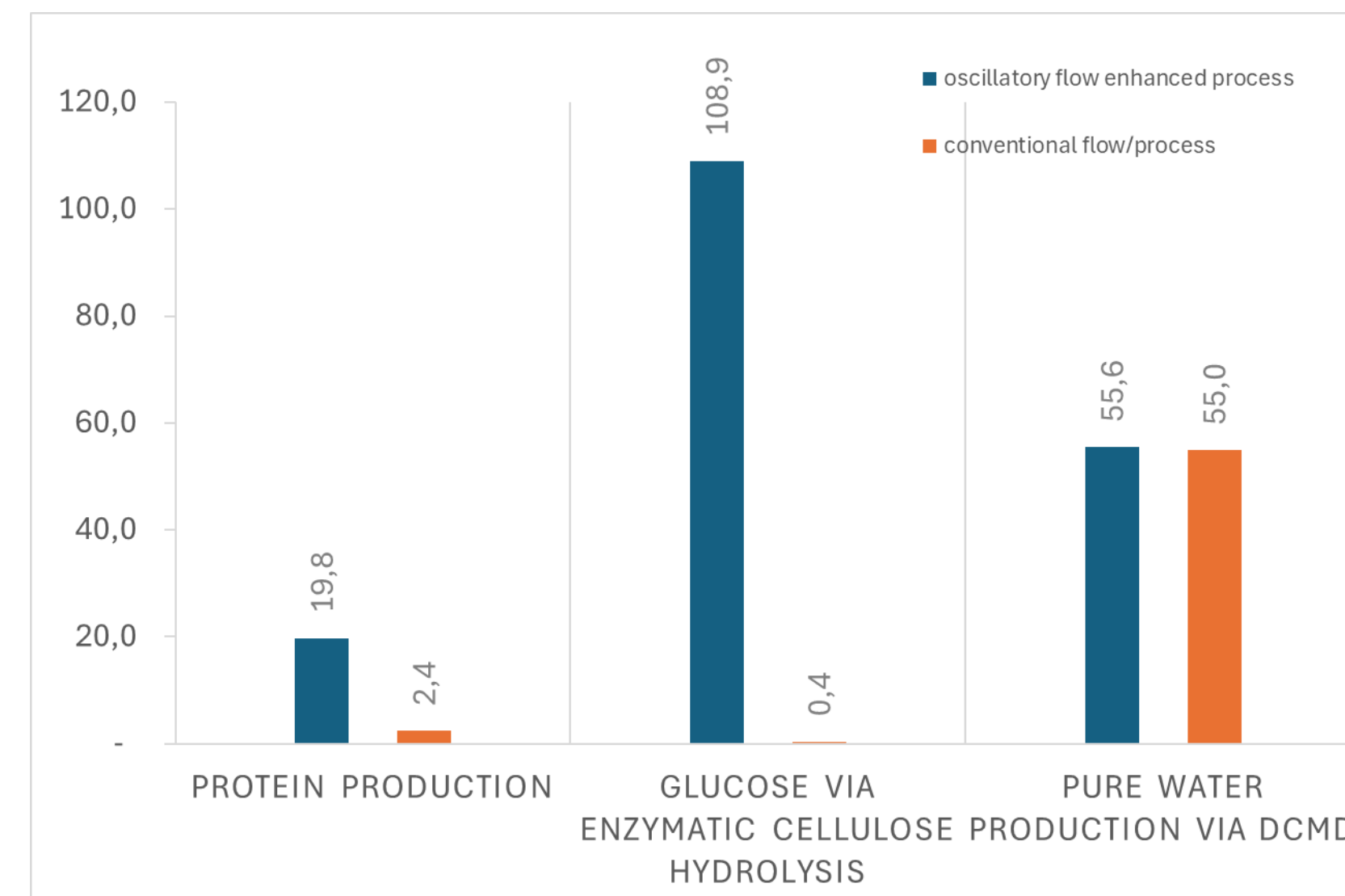
Figure Sources: AEE INTEC, test plant set-up by Höfer and Jeges et al. 2024, data prepared within Cornerstone project by Pane et al. 2025, ECCE/ECCAB poster and Sullman, 2026 Master Thesis performed at AEE INTEC

# Can oscillatory flow debottleneck high energy demand in novel valuable recovery processes?

- High process intensification potential for any extraction, solubilization, absorption process processing thick slurries
- Order of magnitude of energy requirements for OFR processing promising for further scaling and exploitation
- Potential for increasing process and energy efficiency at the same time
- Wide replication potential for any process (residence time ~ >min)

Process Intensification	Factor	Scenario
<b>Increase of Volumetric Productivity</b>	Factor 1.6 BOFB vs. shaking flask	Enzymatic hydrolysis of ligno-cellulosic biomass at same conditions in different operating setups (Shaker, BOFB)
<b>Increase of Volumetric Productivity</b>	Factor 1.5 COFB vs. BOFB	Enzymatic hydrolysis of ligno-cellulosic biomass at same conditions in different operating setups (BOFB, COFB)
<b>Decrease in Residence Time</b>	1.7 x less time to target concentration.	Enzymatic hydrolysis of ligno-cellulosic biomass under same conditions in batch (shaker) and continuous mode of operation.

Buchmaier et al, 2025



## Product per mixing/transporting energy during reaction:

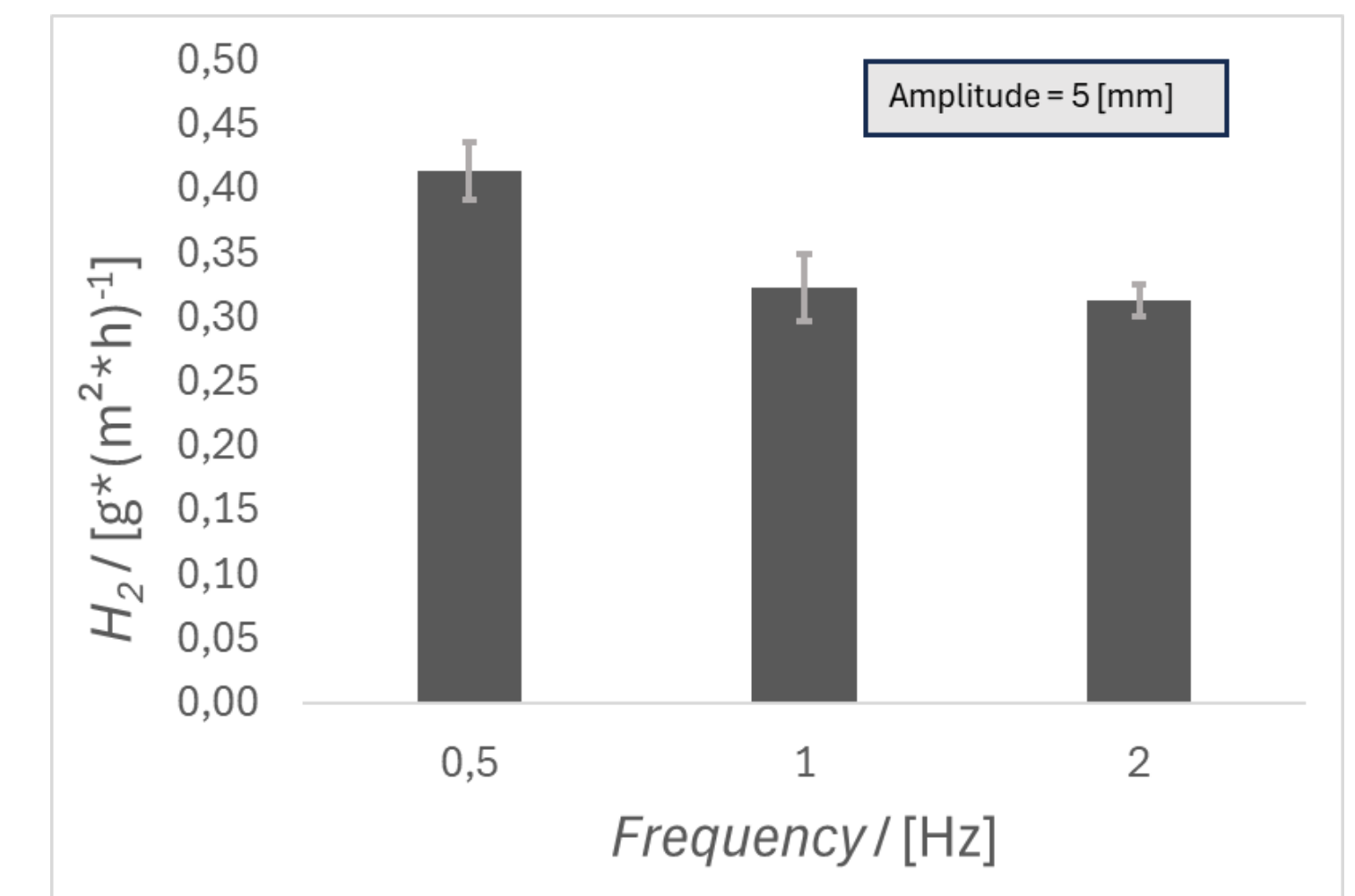
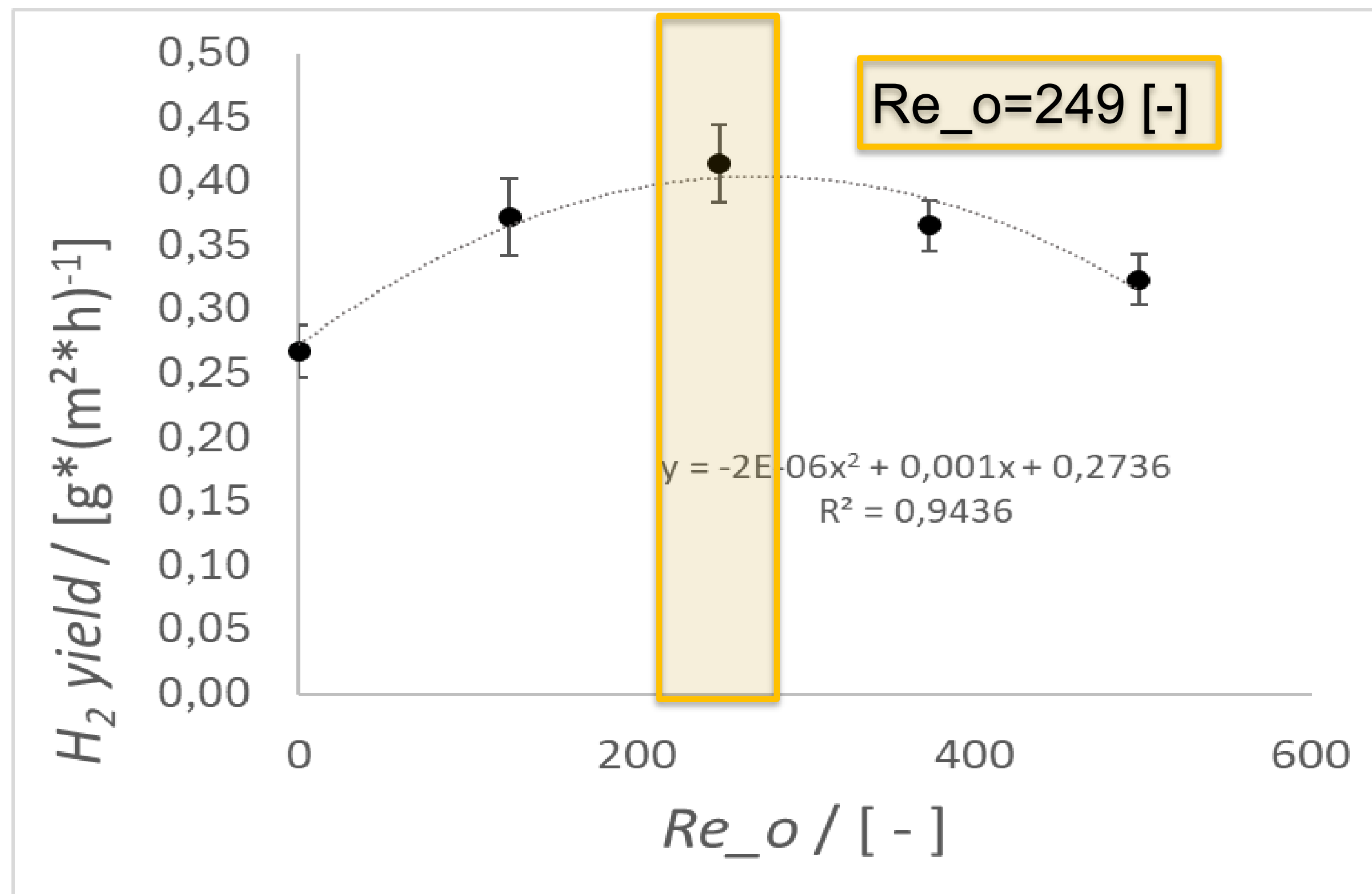
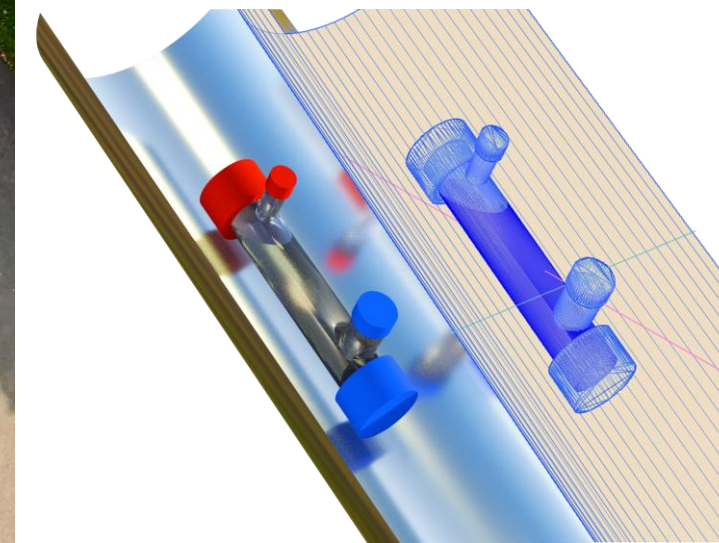
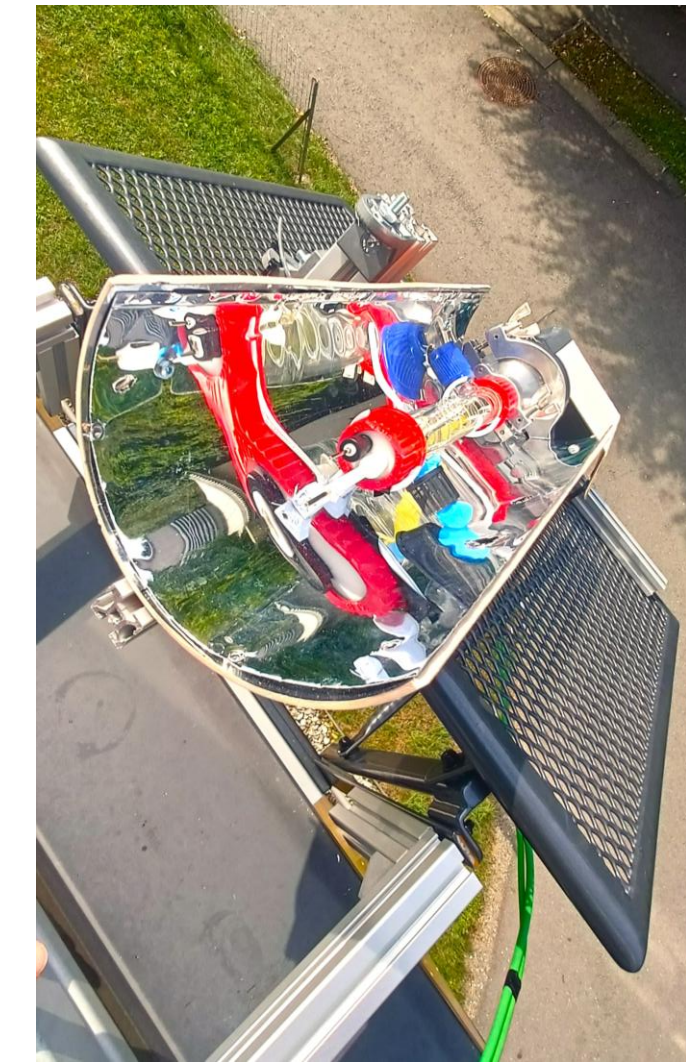
Protein production within OFB per mixing energy efforts (Factor 2 for real mixing efforts assumed) compared to energy demand in beef protein production, Corigliano et al, 2024

Cellulose hydrolysis in OFB compared to STR processing, mixing energy input Correa et al, 2026

DCMD estimated data, measured data with and without oscillatory flow

# Results Real Sunlight: Influence of oscillatory parameters

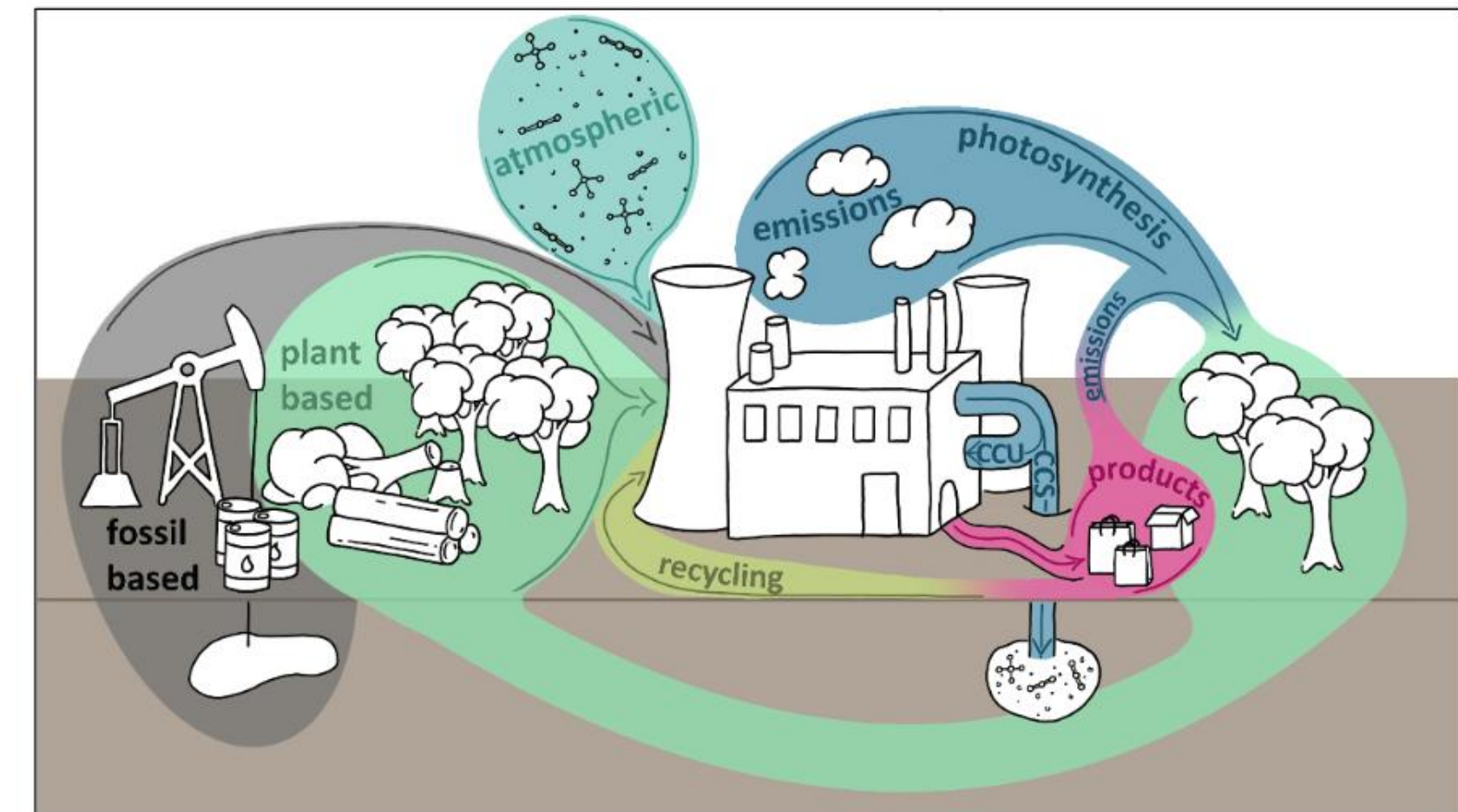
- Highest H<sub>2</sub> yield reached at **Re<sub>o</sub> = 249**
- Frequency shows a higher impact on product yield compared to amplitude



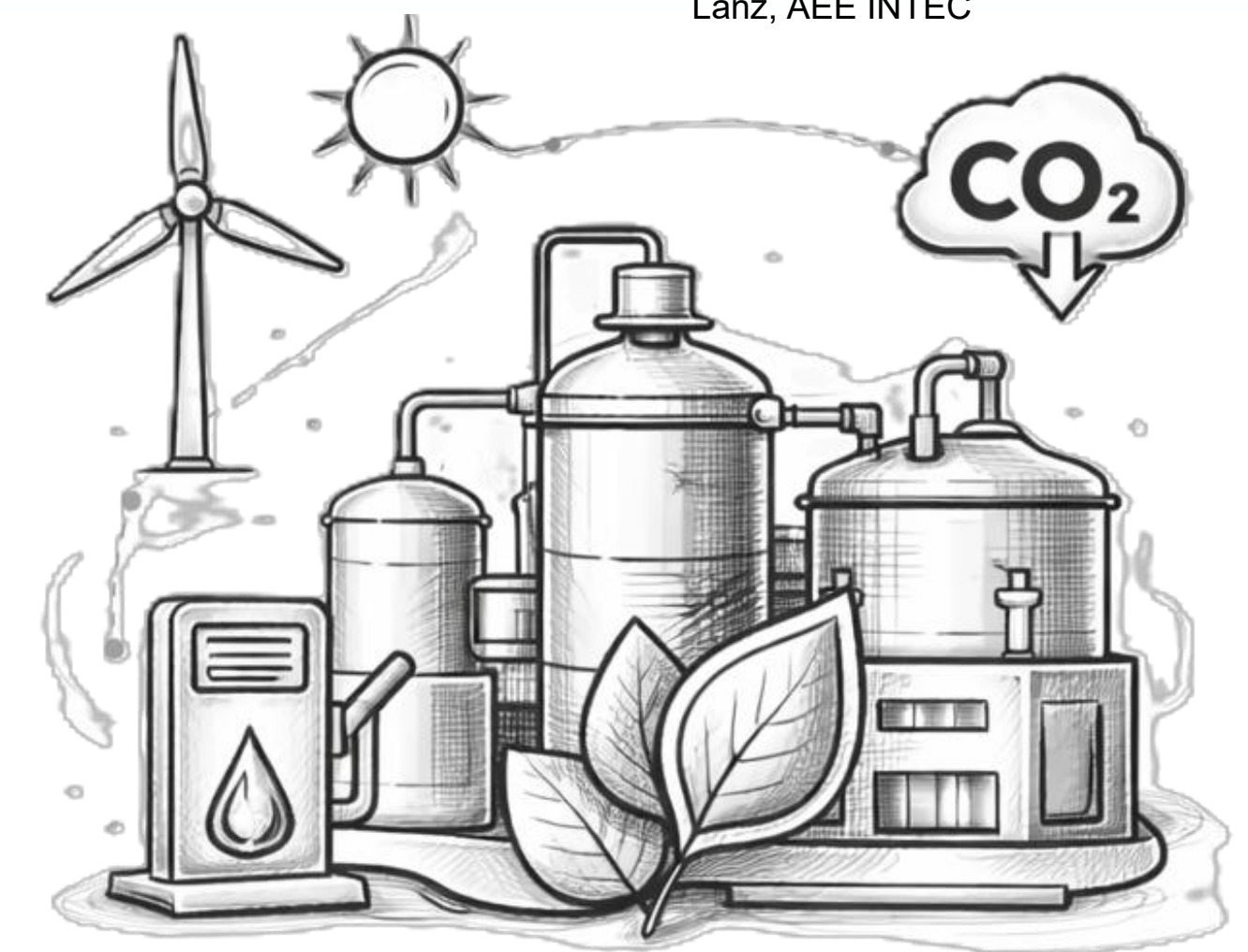
# Conclusions

- **Energy efficiency** is key in circular economy processing
- **Interdisciplinary** between process/chemical engineers and energy experts
- Process intensification considerations can unlock **combined energy and resource efficiency potentials**

...and many further applications of **oscillatory flow**.....



Lanz, AEE INTEC



AEE INTEC, AI enhanced picture



# Acknowledgements



Analytics / Catalyst support:

Manuel Eibisberger, TU Graz  
Group of Dominik Eder and Dogukan Apadiyn, TU Vienna  
Michael Eggermeier, WoodKPlus



Research Group Water- and Process Technologies at AEE INTEC



Funded by the European Union



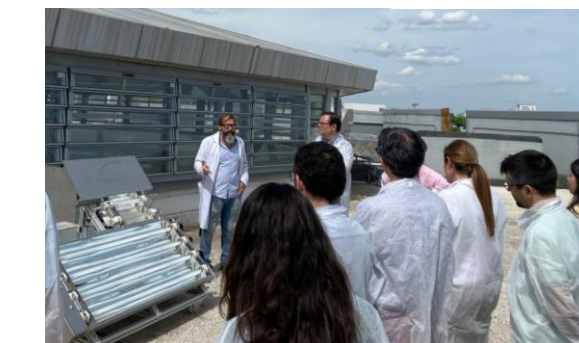
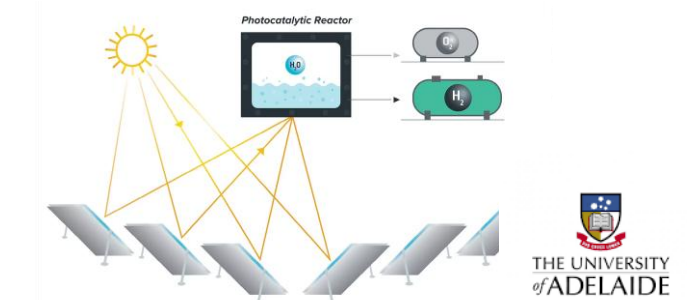
Research funded by



Federal Ministry Republic of Austria Climate Action, Environment, Energy, Mobility, Innovation and Technology



- International Energy Agency Solar Heating & Cooling
- Task: „**Solar photoreactors for the production of fuels and chemicals**”  
(Task Management: Bettina Muster-Slawitsch, AEE INTEC)
  - **Subtask A: Materials and component development**  
(Subtask Lead: Victor de la Peña, IMDEA Energy, Spain)
  - **Subtask B: Solar photoreactor design**  
(Subtask Lead: Sarah Meitz, AEE INTEC, Austria)
  - **Subtask C: System integration**  
(Subtask Lead: Sixto Malato Rodriguez, CIEMAT P.S.A, Spain)
- 40 active experts from 10 countries
- **Need to develop intensified reactors!**



An aerial photograph of a modern building complex. The buildings feature large glass facades and solar panels. A central courtyard with a paved walkway and greenery is visible. The sky is clear and blue. In the top left corner, there is a yellow and blue logo for AEE INTEC. A white box with the text 'IDEA TO ACTION' is overlaid on the image.

**AEE INTEC**

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