Multi-objective optimization of the hydrothermal liquefaction of microalgae for cost-effective advanced biofuels production

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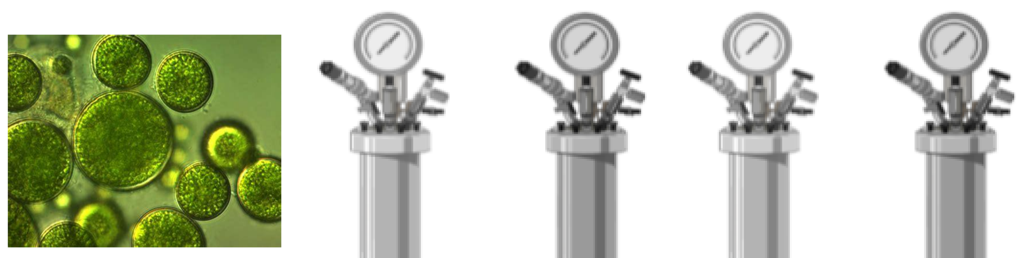
Context

Hydrothermal liquefaction (HTL) converts microalgae into bio-oil, a biofuel precursor that is expected to play a pivotal role in the forthcoming energy transition. **Enhancing the bio-oil productivity and chemical composition is crucial** to ensure compatibility with subsequent upgrading processes and to guarantee the final fuel properties. Nevertheless, operating conditions that enhance bio-oil yield frequently compromise its quality and **the economic implications of energy-intensive, yield-maximizing regimes relative to more balanced strategies remain insufficiently assessed.** Therefore, we present a **multivariable optimization framework** integrating experimental design, process simulation, and techno-economic analysis (TEA) to accelerate a sustainable transition towards biofuels derived from microalgae in small European countries like Belgium.

Methodology

Experimental design

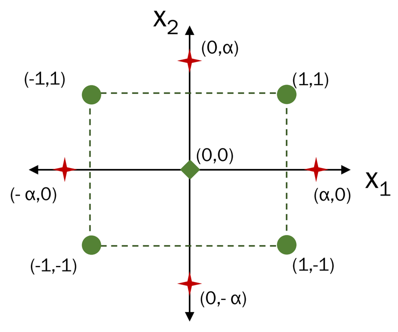


Microalgae

1.a Preliminary screening

- Temperature: 260 – 340 °C.
- Time: 0 – 80 min.

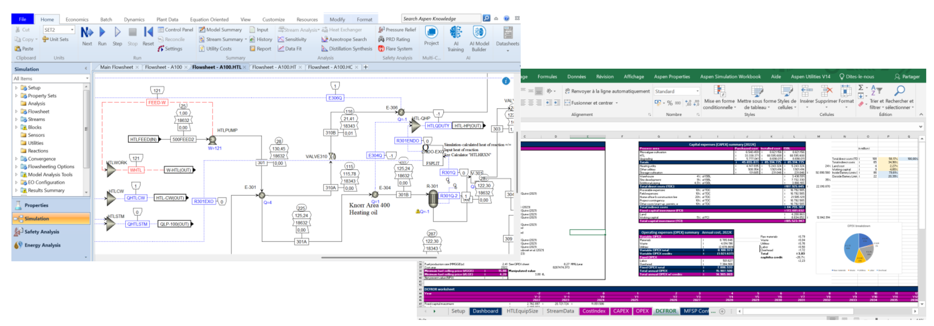
Response variables: bio-oil yield and quality (O/C)



***Expanded to a CCD**

+

1.b Process Simulation



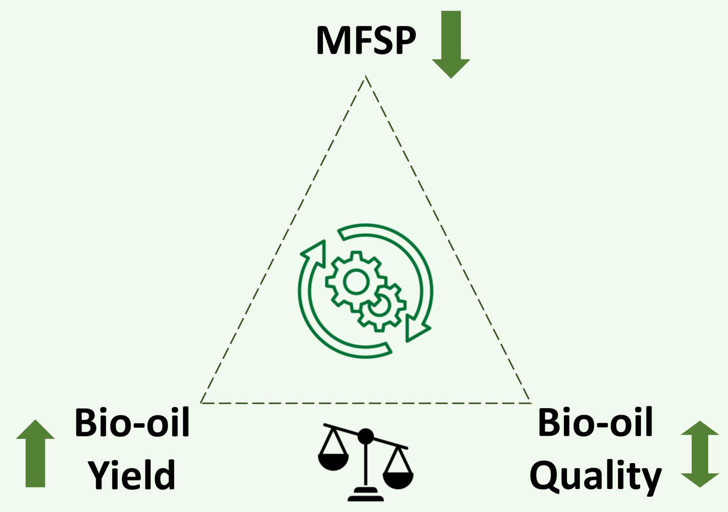
1.c Technoeconomic Assessment

Analysis for 2 production scales:

- Low productivity (LP): 10.9 g/m2/day on 1000-acre.
- High productivity (HP): 17.5 g/m2/day on 5000-acre.

Response variables: Minimal fuel selling price (MFSP) for LP & HP.

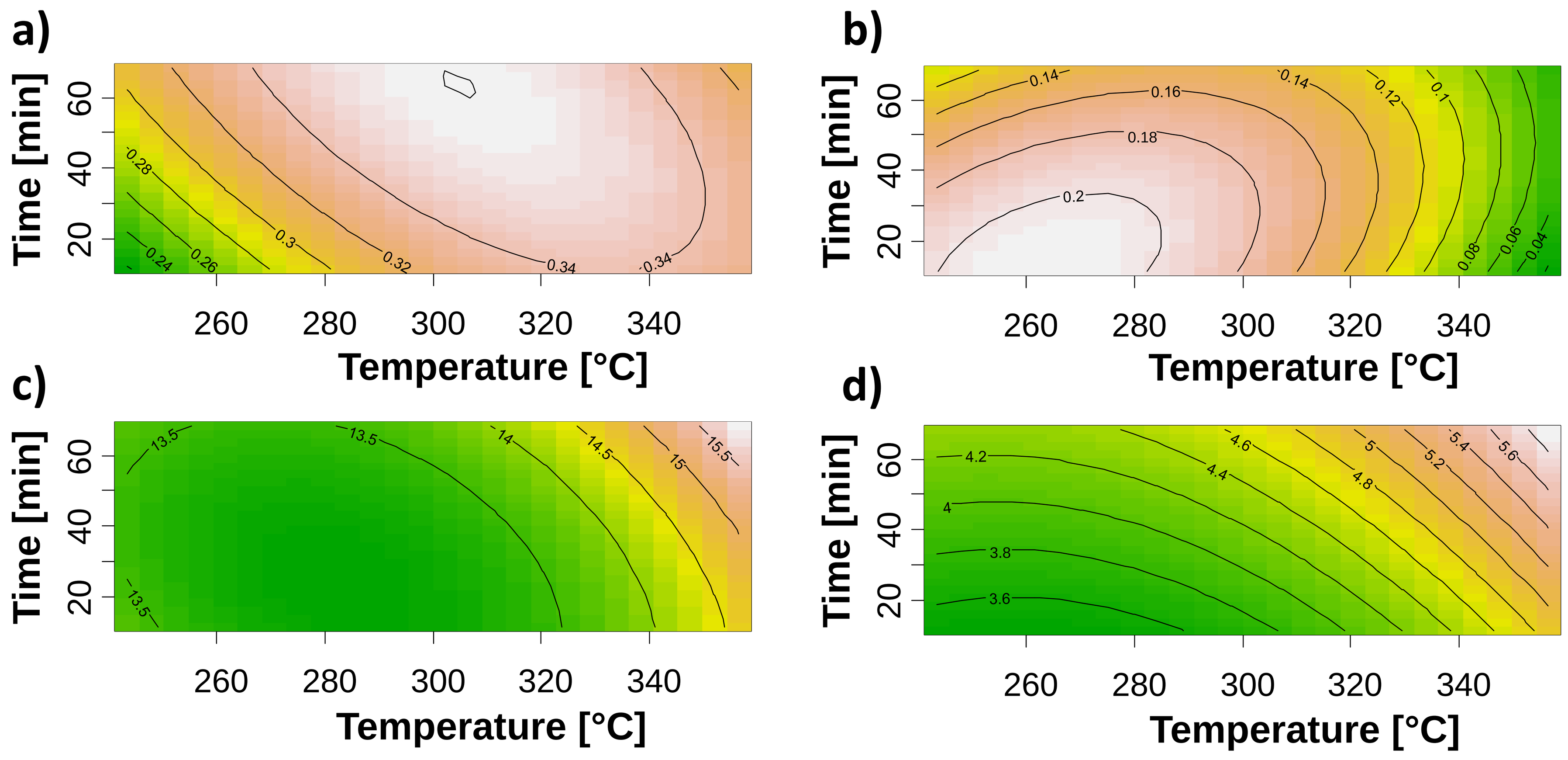
2. Multi-objective Optimization



Optimization following Derringer and Suich desirability functions method.

Results

1. Preliminary screening

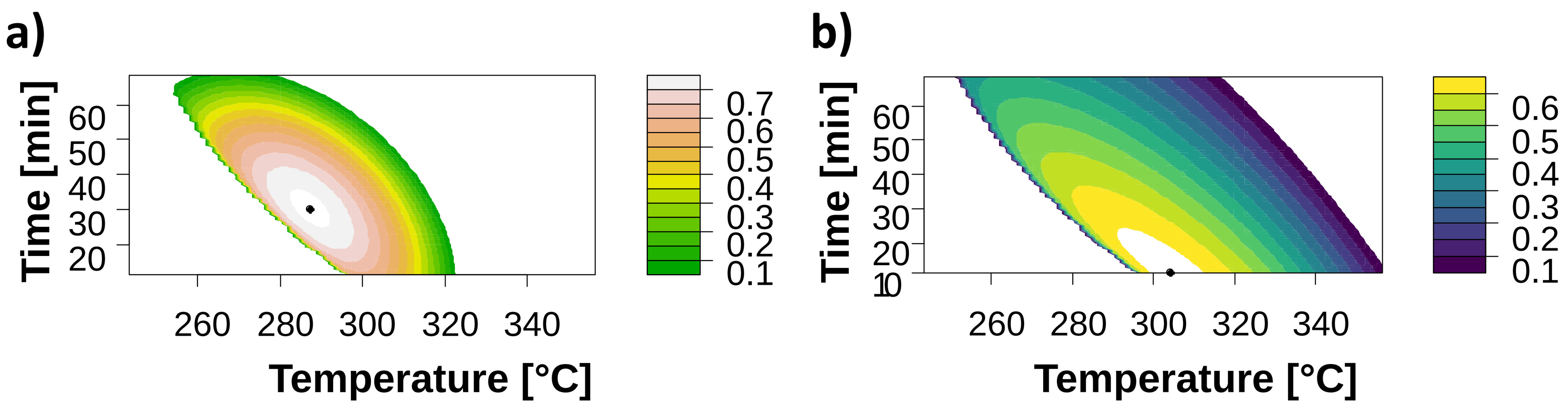


*Contour plots for the different optimal zones: **a)** Optimal region for bio-oil yield, **b)** Optimal region for Bio-oil quality (O/C), **c)** Optimal region for MFSP (low productivity case), **d)** Optimal region for MFSP (high productivity case).*

- Different paths are required to optimize the bio-oil yield, quality (O/C) and the MFSP.
- Increasing the production scale requires lowering the severity of reaction conditions to improve the MFSP.
- Conditions that maximize yield could be exploited to minimize the MFSP for the low productivity case.
- Although abating the O/C demands conditions detrimental to yield and MFSP, complete reduction is not required in HTL.

Results

2. Multi-objective Optimization



Contour plots for the overall desirability for the a) low productivity and b) high productivity cases.

✓ *Stability of the optimal point was proven (wide zones around Max. Desirability)*

Predicted optimal conditions and response variables.

	Low productivity scenario	**High productivity scenario**
Predicted reaction conditions	Temp. = 287.3 °C	Temp. = 304.2 °C
	Time = 30.1 min	Time = 11.7 min
Estimated response variables	Y_{BO} = 0.3326	Y_{BO} = 0.3284
	O/C = 0.1969	O/C = 0.1712
	MFSP = 13.04 €/l	MFSP = 3.77 €/l
Predicted individual desirability	d_{YBO} = 0.7075	d_{YBO} = 0.6258
	$d_{O/C}$ = 0.8324	$d_{O/C}$ = 0.8898
	d_{MFSP} = 0.7569	d_{MFSP} = 0.5513
Predicted overall desirability	D = 0.7639	D = 0.6746

Y_{BO} stands for bio-oil yield.

Single factor optimization (for yield): Temp. = 305.6 °C, Time = 64 min, Yield = 36.00% → MFSP: LP = 13.75 **> 13.04** [€/l]; HP = 4.67 **> 3.77** [€/l]

Technical optimization does not represent best conditions for economical feasibility!

Conclusions

- TEA must be integrated to process optimization.
- Production scale influence the optimization strategy, as energy demands might not be compensated by bio-oil productivity at large scale.
- For land-restricted countries, increasing productivity efficiently is critical. Therefore, the development of cost-effective photo-bioreactors is advised.

Acknowledgments

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