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A model-based combinatorial optimisation approach for energy-efficient processing of microalgae

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ABSTRACT

The analyses of algae biorefinery performance are commonly based on fixed performance data for each processing step. In this work, we demonstrate a model-based combinatorial approach to derive the design-specific upstream energy consumption and biodiesel yield in the production of biodiesel from microalgae. Process models based on mass and energy balances and conversion relationships are presented for several possible process units in the algae processing train. They allow incorporating the effects of throughput capacity and process conditions, which is not possible in the data-based approach. Therefore, the effect of choices in the design on the overall performance can be quantified. The process models are organised in a superstructure to evaluate all combinations of routings. First, this is done for selected fixed design conditions, which is followed by optimisation of the process conditions for each route by maximising the net energy ratio (NER), based on upstream energy consumption and biodiesel yield. A scenario based on current energy production and state-of-the art techniques for algae processing is considered. The optimised process conditions yield NER values which are up to about 30% higher than those for fixed process conditions. In addition, the approach allows a quantitative bottleneck analysis for each process route. The model-based approach proves to be a versatile tool to guide the design of efficient microalgae processing systems.

1. Introduction

Producing biodiesel from microalgae biomass requires the processing steps harvesting, dewatering, disruption, extraction and lipid conversion. Various processing units are available, ranging from traditional ones like centrifugation and filtration to innovative algae specific processing units such as microwave assisted conversion [1]. Table 1 gives an overview of possible processing units for each main step in the processing to biodiesel. In the process design, several combinations of processing units are possible. Usually, process engineers use a step-wise approach to design process routings, whereby for every function the unit with the best performance is chosen. However, each choice in the route affects the performance of units downstream. As a consequence, an early choice may have a negative effect on process units further in the processing route.

The processing of algae biomass has an important role in the sustainability performance of algae biodiesel production. Several authors evaluate the energy use and other impacts of processing options in environmental assessment studies such as life cycle assessments (LCA), as is shown in Table 2. Each study considers a specific processing route and assumes a specific lipid content. In addition, some consider allocation of energy to co-products, which decreases the energy use for biodiesel production. In these works, standard characteristics of processing units are employed and basic processing routes with limited variation are studied. Brentner et al. [2] recognised the limitations of such an approach and studied all possible combinations of units that can be applied in the processing of algae. In that study the route of chitosan flocculation followed by supercritical methanol conversion was evaluated as best, with the lowest use of water and energy.

All the authors above, including Brentner et al., use an approach whereby the performance of single process units is derived from standard databases and literature. The disadvantage is that the overall performance of the routes is not affected by process conditions or other decision variables. The next example illustrates the relevance to include the process conditions in the performance analysis. Algae solutions are often first concentrated 10 times, followed by dewatering to reach a solid concentration above 15% [9]. An algae solution of 4 g L^{-1} would thus get 10 times concentrated during harvesting and 4 times during dewatering. However, other combinations of concentration factors are possible. The energy requirement for two centrifuges in series, with different combinations of concentration factors was calculated based on Wileman et al. [10]. Fig. 1 shows that the lowest energy requirement is obtained with 4 times concentration during harvesting

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Table 1
Overview of some possible processing units for biodiesel production from algae.

Harvesting	Dewatering	Disruption	Extraction	Conversion
Centrifugation	Centrifugation	Bead milling	Traditional solvent (hexane)	Acid catalyst
Pressure filtration	Pressure filtration	High pressure homogenisation	Mixed solvent	Alkali catalyst
Vacuum filtration	Vacuum filtration	Ultrasound	Supercritical CO_2	Heterogeneous catalyst
Tangential cross flow filtration	Drying	Supersonic wave treatment	Ionic liquids	Enzymatic with lipases
Ultrasound sedimentation	Steam evaporation	Pulsed electric field	Two-phase systems	
Chemical flocculation		Acid treatment	Switchable solvents	
Biological flocculation		Enzymatic cell wall degradation	Surfactants	
Autoflocculation				
Dissolved air flotation				
Suspended air flotation	Supercritical methanol extraction and conversion			
Electrolytic flotation			Microwave assisted extraction and conversion	

and subsequently 10 times concentration during dewatering. The energy saving is 38%, compared to the customary 10 × 4 treatment.

An alternative for the data-based approach is a model-based approach. Hereby, the characteristics of the flows, for example flow rate, algae concentration and lipid content, are linked to the mass and energy balances for every processing unit. By connecting the models of all processing units, the performance of each route can be quantified and optimised with respect to the routing and operating conditions [8,11].

In this work, the model-based approach for combinatorial evaluation of several process options is demonstrated. The performance is expressed as net energy ratios (NER), i.e. in this case the energy in the biodiesel divided by the total upstream energy demand for processing, which is the total energy needed to produce the required amounts of electricity and heat. A scenario based on current energy production and state-of-the art techniques for algae processing is considered. This includes the recovery of heat and the use of natural gas for generating electricity and heat.

The results illustrate the performance of groups of processing units using optimised operating conditions.

2. Model-based combinatorial approach

The calculation steps of the model-based combinatorial approach are illustrated in Fig. 2. First, a selection of process units is made, which are then grouped in a superstructure. This superstructure indicates all feasible process routes. In the second step, process models are developed for each of the process units in the superstructure. Mass and energy balances are used together with additional relations to connect the process yields and energy use with the processing conditions. Two approaches are available in the third step. One is to calculate the biodiesel yield and upstream energy consumption of each route, based on given fixed process conditions. The other approach is to improve the process design by optimising process conditions in such a way that the highest ratio of biodiesel yield and upstream energy consumption is obtained.

The selections and calculations are further discussed in the sections below.

2.1. Superstructure and processing units

The selection of processing units for biodiesel production from algae is based on the availability of process relations and data. It contains both traditional and innovative process units. Fig. 3 shows the superstructure. The traditional processes have proven their success in other applications, like food and biotechnology. However, the process conditions of these traditional methods should be optimised for algae. Innovative processes are more specifically developed for algae or combine several processing steps. This mostly results in a lower energy consumption and less room for improvement. In the superstructure, the feasible routes are indicated by connecting lines. For example, bead milling can be followed by hexane, supercritical CO_2 extraction, or enzymatic conversion, but not by microwave assisted dry conversion.

The processing starts with harvesting to separate microalgae from the cultivation solution. Six process units are considered for the harvesting step. In "mechanical harvesting" steps energy is applied to separate the algae from the cultivation solution; this includes centrifugation, vacuum filtration, pressure filtration and ultrasound sedimentation.

Table 2
Literature overview of direct energy requirements for processing microalgae to biodiesel.

Cultivation based on	Lipid content	Processing route	Direct energy requirement (GJ metric ton^{-1} biodiesel)	Co-product allocation included?	Reference	Scenario name
Raceway pond	25%	Centrifugation – drying – pressure filtration – hexane extraction – esterification	255	No	[2]	Base
Flat panel PBR	25%	Chitosan flocculation – supercritical methanol extraction and conversion	44	No	[2]	Best
Raceway pond	18–39%	Flocculation – rotary press – belt drying – oil milling – hexane extraction – transesterification	100–46	No	[3]	Dry
Raceway pond	18–39%	Flocculation – rotary press –oil milling – hexane extraction – transesterification	32–15	No	[3]	Wet
Flat panel PBR	50%	Centrifugation – shear mixing – hexane extraction – conversion	23	No	[4]	
Raceway pond	23%	Centrifugation – cell lyses – solvent extraction – methanol conversion	41	Yes	[5]	
Raceway pond	40%	Settling tank – drying – hexane extraction – conversion with acidic catalysis	34 [a]	No	[6]	Base
Raceway pond	40%	Settling tank – drying – hexane extraction – conversion with acidic catalysis (with energy and material integration)	23 [a]	No	[6]	Integrated
Raceway pond	25%	Bioflocculation – dissolved air flotation – centrifugation – homogeniser – hexane extraction	23 [a]	No	[7]	
Raceway pond	20–50%	Centrifugation – thermal drying – hexane extraction – transesterification – anaerobic digestion	44–33 (with 25–75% probability)	Yes	[8]	Reference
PBRs and raceways combined	20–50%	Bed drying – wet lipid extraction – hydrotreating – anaerobic digestion	23–17 (with 25–75% probability)	Yes	[8]	Innovative

[a] Energy requirement includes cultivation.