Algal Research 31 (2018) 347–362

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Techno-economic evaluation of microalgae harvesting and dewatering systems

F. Fasaei, J.H. Bitter, P.M. Slegers, A.J.B. van Boxtel*

Biobased Chemistry and Technology, Wageningen University Research, P.O. Box 17, 6700AA Wageningen, The Netherlands

ARTICLE INFO

Keywords:
Microalgae
Harvesting
Dewatering
Cost
Energy
System analysis

ABSTRACT

Microalgal biomass is processed into products by two main process steps: 1) harvesting and dewatering; and 2) extraction, fractionation and conversion. The performance of unit operations for harvesting and dewatering is often expressed in qualitative terms, like "high energy consumption" and "low in operational cost". Moreover, equipment is analysed as stand-alone unit operations, which do not interact in a chain of operations. This work concerns a quantitative techno-economic analysis of different large-scale harvesting and dewatering systems with focus on processing cost, energy consumption and resource recovery. Harvesting and dewatering are considered both as a single operation and as combinations of sequential operations. The economic evaluation shows that operational costs and energy consumption are in the range 0.5–2 €·kg^{-1} algae and 0.2–5 kWh·kg^{-1} of algae, respectively, for dilute solutions from open cultivation systems. Harvesting and dewatering of the dilute systems with flocculation results in the lowest energy requirement. However, due to required chemicals and loss of flocculants, these systems end at the same cost level as mechanical harvesting systems. For closed cultivation systems the operational costs decrease to 0.1–0.6 €·kg^{-1} algae and the energy consumption to 0.1–0.7 kWh·kg^{-1} algae. For all harvesting and dewatering systems, labour has a significant contribution to the total costs. The total costs can be reduced by a high level of automation, despite the higher associated investment costs. The analysis shows that a single step operation can be satisfactory if the operation reaches high biomass concentrations. Two-step operations, like pressure filtration followed by spiral plate technology or centrifugation, are attractive from an economic point of view, just as the operation chain of flocculation followed by membrane filtration and a finishing step with spiral plate technology or centrifugation.

1. Introduction

The increasing demand for food, energy and materials raised the role of microalgae feedstock in the biobased economy. However, commercial production of algal products is still in its infancy. To commercialize algal biomass as a commodity, the production costs for algal products should be decreased at least by a factor 10 [1].

The production of algal based products has three main steps: 1) biomass cultivation, 2) harvesting and dewatering, and 3) biomass extraction, fractionation and conversion. Algal biomass cultivation occurs in open or closed photobioreactors. These reactors deliver a very dilute algal solution ranging from 0.05–0.075% dry matter for open pond systems to 0.3–0.4% for closed systems. The function of harvesting and dewatering is to increase the total solid matter up to 10–25% of total dry matter [2] or even to a dry product. Harvesting and dewatering can be done in one or more successive steps, depending on the type of applied equipment. In the last stage of processing, the harvested biomass is split into fractions towards the aimed components, like lipids, proteins and carbohydrates. Furthermore, specific components of interest are processed into user products, such as biodiesel from lipids.

Cultivation is the main cost contributor for algal based products [3,4]. However, harvesting and dewatering of microalgae biomass are also considered as an important contributor to the total costs. Several studies report the harvesting costs at 20–30% of the total production costs [2,5–8]. The high capital expenditure and energy consumption result from the dilute algae solutions, the large volumes to be processed, and the small size of microalgal cells [1,5,9].

Various unit operations show potential to be implemented for harvesting and dewatering. These technologies range from proven technologies to innovative process unit operations. Application of the technologies is not straightforward due to the physical and chemical properties of dilute algal solutions. Table 1 gives an overview and qualifications, from existing literature, of possible unit operations for harvesting and dewatering. Harvesting and dewatering of algal biomass can be carried out by using a single technology with high impact

* Corresponding author at: P.O. Box 17, 6700 AA Wageningen, The Netherlands.
E-mail address: ton.vanboxtel@wur.nl (A.J.B. van Boxtel).

https://doi.org/10.1016/j.algal.2017.11.038
Received 29 June 2017; Received in revised form 29 November 2017; Accepted 30 November 2017

Table 1
Overview of available technologies for harvesting and dewatering of microalgae with main qualifications.

Technology	Strength	Weakness	Reference
Centrifugation	• Continuous • Efficient for large scale processing • High recovery	• High capital cost	[2,9]
Spiral plate technology (SPT)	• Efficient for small scale processing • High recovery	• High capital cost • Limited throughput capacity	[9,11]
Pressure filtration	• Low energy demand • High recovery	• Discontinuous • Clogging or fouling	[5,12,13]
Vacuum filtration	• Continuous	• Relative high harvesting cost • Clogging or fouling	[5,12–14]
Membrane filtration	• Efficient for small scale processing • High recovery	• Fouling • High capital cost	[15–19]
Sedimentation	• Easy application • Low energy demand	• Slow rates • Large operational area • Low recovery • Limited application: suitable for large size algae	[9,16,20]
Chemical flocculation	• Low energy demand • Low equipment cost	• Difficult recovery of flocculants	[13,16,21,22]
Drum drying	• Mature technology	• High energy demand	[23]
Spray drying	• Suitable for high value products	• High energy demand	[5,24]
Solar drying	• Low cost	• Large drying surface • Slow drying rate • High risk for contamination and loss of mass • Not for food grade products	[8,25]

performance or by combining multiple unit operations in a sequence. The effectivity of combination of unit operations in sequence depends on the individual performance of each unit. The choice of a unit operation for the first concentration step or harvesting also affects the choice and performance of the following units in the dewatering step [10].

Fig. 1 shows a structure of possible combinations of unit operations. Concentrating microalgae from the cultivation medium can follow three strategies: 1) a single-step harvesting and dewatering to the aimed concentration; 2) one step of harvesting followed by a separate dewatering step; and 3) one step of harvesting followed by two steps of dewatering. These three strategies can be followed by drying to extend the shelf-life and to make the product accessible for further downstream processing [5]. The choice for the strategy is also set by the constraints of an operation, such as the maximal feasible concentration, the viscosity of the concentrate, etc. For example, flocculation is effective up to 2–2.5% dry matter [22,26–28] and membrane filtration to 5–7% dry matter [29]. These operations need a third operation to reach a final concentration of 10–25% dry matter, as a result of the mentioned constraints.

Sedimentation, driven by the gravitational force, has long settling times (10 h or longer) and can reach only total solid contents up to 2–3% [9]. Therefore, this method is not attractive for large scale applications [20] and is outcompeted by flocculation. Solar drying is also slow, requires large areas and has a high risk for contamination and loss of biomass [8,25]. Therefore, these technologies are not given in Fig. 1 as options for processing algal biomass in large scale applications.

Harvesting and dewatering are often assessed qualitatively (e.g. qualifications used in Table 1) or papers report experimental results of just a single unit operation [2,9,30,31]. Generally, quantitative assessments of technologies for harvesting and dewatering focus on energy demand and yield [31]. A common drawback of existing evaluations is due to the stepwise approach. In this type of approach, each technology is considered for a specific task, while the interaction of all operations in a chain, and subsequent overall performance, are not evaluated or discussed. The main goal of this study is, therefore, to quantitatively analyse combinations of harvesting-dewatering systems. This quantitative analysis is based on a techno-economic assessment of harvesting and dewatering systems available at industrial scale. In this analysis, feasible configurations of proposed unit operations, as given in Fig. 1, are considered. The main addressed criteria are biomass recovery, energy requirement, capital, labour and other operational expenditures per kg of harvested biomass. Moreover, aspects such as chemical consumption, resource recovery and opportunities to recycle the medium to cultivation site are discussed. In an effect analysis, the role of different feed concentrations obtained in different cultivation systems, the role of seasonal changes, production characteristics related to the latitude, and the role of automation are discussed. The results of the analysis gives a clear view on the efficiency of harvesting-dewatering processing chains in terms of cost, energy consumption, and resource recovery.

2. Approach and methods

Fig. 1 illustrates the succeeding steps and unit operations that are applied for harvesting and dewatering in this work. The available technologies for the harvesting step are membrane filtration, chemical flocculation, vacuum and pressure filtration, centrifugation, and spiral plate technology. For dewatering step, membrane filtration, vacuum and pressure filtration, centrifugation, and spiral plate technology, can be applied. A short description of the technologies is given in Appendix A. Technologies, such as centrifugation, vacuum and pressure filtration and spiral plate technology, have the potential to achieve high biomass concentrations and possibly do not need an additional dewatering step. Membrane filtration and flocculation are limited in the maximal concentration and require a successive step (centrifugation, vacuum or pressure filtration or spiral plate technology) to achieve a high concentration solution. Moreover, an initial harvesting step reduces the volume size significantly and it is, therefore, meaningful to quantify the role of volume reduction on the performance of a chain of operations.

2.1. Model based analysis

A model-based approach is applied for the techno-economic evaluation. For each unit operation a simulation model is defined. The models concern the input-output mass and energy balances for each unit operation. Additional relations are included to connect the energy demand and product yield to economic estimation elements (see Appendices B and D). The models for the unit operations are made in Excel. A flexible structure is used to connect all unit operations with each other in any combination, as given in Fig. 1.

The function of harvesting and dewatering is to split feed streams,