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A Tool for Modelling of One- or Two-Step Microalgae Harvesting Processes

Martina Hladíková*, Radek Šulc

Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Process Engineering, Technicka 4, 160 00, Prague 6, Czech Republic
Martina.Hladikova@fs.cvut.cz

Separation of microalgae from aqueous solutions still requires further optimization and knowledge. The tool for modelling of one- or two-step microalgae harvesting technology should provide a way to predict the final concentration of microalgal suspensions. The presented spreadsheet-based tool enables to determine the mass balance of the separation process and other parameters required for the equipment basic design. These parameters are the mass flow rate of individual media, an agent consumption, and the estimation of energy consumption. The tool allows a user to combine different separation processes of various separation efficiencies. A pretreatment by coagulation or flocculation before the separation process can be also included. The applicability of this approach was demonstrated on three cases.

1. Introduction

Harvesting of microalgae is an energy-intensive and expensive part of the production of microalgal biomass due to the necessity to separate a large volume of culture medium from microalgal suspensions. According to the Barros et al. (2015), the harvesting process usually accounts for about 20 to 30% of the total cost. Unlike this, Fasaei et al. (2018) estimated the share of harvesting cost in the range from 3 to 15 % of total production costs. They reported the cost range from 0.3 to 2 € kg^{-1} algae and the energy consumption up to 4.5 kWh kg^{-1} algae for the treatment of 0.05 % cultivation suspension (an open cultivation system) to 15 % dry matter. Increasing the cultivation concentration combined with a lower feeding shifts, the energy consumption towards to lower values. They reported the production cost below 0.5 € kg^{-1} algae and the energy consumption below 0.5 kWh kg^{-1} algae for the treatment of the algae suspension cultivated in closed cultivation systems (1.5 ÷ 2.5 kg m^{-3}).
Selection of the adequate harvesting technology depends on many factors, mainly on the characteristics of the target microorganism and on the type and value of the end product (Barros et al., 2015). Al Hattab et al. (2015) used the following criteria: (a) dewatering efficiency, (b) cost, (c) toxicity, (d) suitability for a large-scale use, (e) time, (f) species specificity, (g) reusability of media and (h) maintenance for the evaluation of 16 harvesting techniques applied for biodiesel production in an industrial scale.
To achieve the highest possible final concentration of the microalgal suspension, the two-step harvesting process is considered more effective than the one-step harvesting process. The first step of the two-step harvesting process, commonly referred to as thickening, is used to remove a large amount of culture medium, hereinafter referred to as water. For this stage, cheaper harvesting technologies, such as gravitational sedimentation or flotation are used. Belohlav and Jirout (2019) developed a methodology for the equipment basic design of gravitational settlers based on the measured settling velocity and the distribution of microalgae cells. The operational parameters of various flotation techniques are presented in more detail in Hladíková and Šulc (2021). The second step is performed by a more energy-intensive and expensive technology, such as centrifugation or filtration. Abu-Shamleh and Najjar (2020) identified eight factors with the potential to affect the energy consumption of the disc-stack centrifuge. They found that the particle size, the rotational speed, and the outer radius of the centrifuge are the main three factors that have the largest impact on the energy consumption of the centrifuge. Membrane filtration for microalgae harvesting has been used both in a single-step and two-step process (Bilad et al., 2014). The harvesting performance should be improved by coagulation and flocculation.

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Various computational approaches are used in various technico-economic studies to obtain rigorous mass balances. Davis et al. (2011) used ASPEN software for a techno-economic analysis of autotrophic microalgae for fuel production. Riós et al. (2013) combined ASPEN software, MATLAB software, and a spreadsheet model for the modelling of different scenarios of harvesting, oil extraction, and transesterification of lipids for biodiesel production. The ASPEN software was used for modelling of oil extraction and lipid transesterification. The harvesting was modelled by a spreadsheet model. The MATLAB software was used for the interaction and data exchange between all modules. The special and complex software, such as ASPEN and MATLAB, are relatively easily available for academic purposes and for commercial purposes of large companies. Therefore, there is an opportunity for spreadsheet-based tools for their simplicity and availability for a wide group of users.
This work aims to create a simple spreadsheet-based tool for process modelling of one- or two-step harvesting processes enabled to determine the parameters for the equipment basic design, such as the mass flow rates of individual components, the agent consumption, the final concentration of the microalgal suspension, and the estimation of energy consumption for the following input data: the input volumetric flow rate of the microalgal suspension, the input concentration of the microalgal suspension and the efficiencies of individual harvesting methods. The process model also implements a coagulation/flocculation technique as a pretreatment method. For the mass balancing, the methodology proposed by Ditl and Netušil (2018) was adopted and applied.

2. Separation process: tool overview

The separation process is performed at the end of the exponential growth phase of the phototrophic microalgal cultivation. This process model consists of 3 stages: i) pretreatment, ii) separation technique 1 (noted as Separation 1) and iii) separation technique 2 (noted as Separation 2). The block scheme of the algal technology from cultivation to utilization is shown in Figure 1. The balanced harvesting technology is defined by the balancing boundary. The streams and present components are described in Table 1. The harvesting technology can be configured as a single-stage or two-stage process. In case of the one-step harvesting process, just Separation 1 is performed. In case of the two-step harvesting process, both separation stages are performed. Separation 1 and Separation 2 refer to various separation processes which can be used to harvest microalgae from aqueous solutions. The used separation processes are defined by a user.
Optionally, a pretreatment by coagulation or flocculation of the microalgal suspension can be included. A coagulant or flocculant, hereinafter referred to as an agent, can be applied to enhance the entire separation process. During this stage, the agent is mixed with water in a stirred vessel and the mixture is transported to a static mixer. In the static mixer, the mixture of the agent and the microalgal suspension are mixed. Aggregates of microalgae cells are formed. The pretreatment has a positive effect on the harvesting efficiency of the following separation processes.
Considered balanced components are biomass, coagulant or flocculant, and water. The numbering of defined components is presented in Table 2. The following terms microalgal suspension and input microalgal suspension are used in the next sections with this meaning: i) the microalgal suspension consists of biomass, agent and water, and ii) the input microalgal suspension consists of biomass and water. The spreadsheet tool utilizes MS EXCEL software.

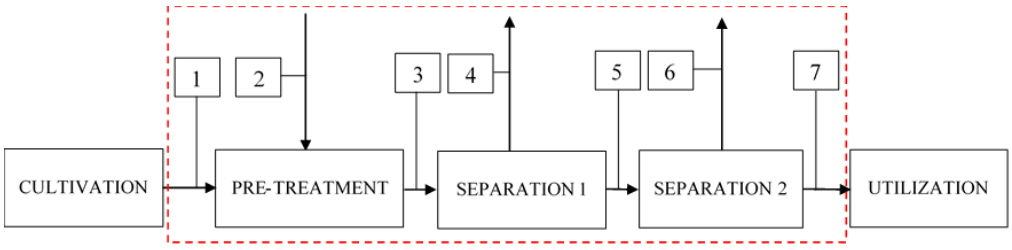

Figure 1: The block scheme of the balanced harvesting technology defined by a balancing boundary (the red dashed line)

The following assumptions are considered for the presented cases:

- Density of the cultivation medium is 1,000 kg m^{-3}
- Streams no. 4 and 6 contain only water
- The added amount of coagulant/flocculant is directly proportional to the concentration of the microalgal suspension
- If coagulation/flocculation is applied, a solid agent is mixed with water in a stirred vessel, and the agent concentration of 0.1 % w/w is considered in the final aqueous solution

Table 1: Balancing tool: the definition of streams and their composition

Number of the stream	Description of the stream	Component
1	microalgal suspension feed	biomass, water
2	agent feed (aqueous solution)	an agent, water
3	feed of Separation 1 unit	biomass, an agent, water
4	water removed by Separation 1	water
5	feed of Separation 2 unit	biomass, an agent, water
6	water removed by Separation 2	water
7	microalgal suspension outflow	biomass, an agent, water

Table 2: Balancing tool: the definition of components

Number	Component
1	biomass
2	an agent
3	water

Based on the following input parameters, the mass balance is calculated:

- Separation line performance ($m^3\ h^{-1}$)
- Concentration of the microalgal suspension entering the separation line ($g_{mic}\ L^{-1}$)
- Density of the microalgal suspension (kg m^{-3})
- Dosage of coagulant/flocculant if applied (kg)
- Efficiency of separation process 1 (%)
- Efficiency of separation process 2 if applied (%)

3. Mass balance calculation

The mass balance calculation is based on the mass balance approach proposed by Ditl and Netušil (2018). Using this methodology, the mass flow rates of individual components and the stream composition were determined.

The steady state was assumed, i.e., the sum of the mass flow rates of input streams equals to the sum of the mass flow rates of output streams. Mass balance in individual process units is described, in general, by the equation Eq(1), where $\dot{m}_{j,i\_IN}$ (kg h^{-1}) is the mass flow rate of the i^{th} medium in the j^{th} stream entering a process unit and $\dot{m}_{j,i\_OUT}$ is the mass flow rate of the i^{th} medium in the j^{th} stream leaving a process unit.

$$\sum \dot{m}_{j,i\_IN} = \sum \dot{m}_{j,i\_OUT} \quad (1)$$

In the following text, all equations required for the mass balance calculation are listed. Total mass balance in the pretreatment unit, separation unit 1, and separation unit 2 is described by the following equations Eq(2), Eq(3), and Eq(4), respectively:

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \quad (2)$$

$$\dot{m}_3 = \dot{m}_4 + \dot{m}_5 \quad (3)$$

$$\dot{m}_5 = \dot{m}_6 + \dot{m}_7 \quad (4)$$

Mass balance of components in the pretreatment unit is calculated for biomass by Eq(5), for an agent by Eq(6), and for water by Eq(7):

$$\dot{m}_{1,1} = \dot{m}_{3,1} \quad (5)$$

$$\dot{m}_{2,2} = \dot{m}_{3,2} \quad (6)$$

$$\dot{m}_{1,3} + \dot{m}_{2,3} = \dot{m}_{3,3} \quad (7)$$

Mass balance of components in the separation unit 1 is calculated for biomass by Eq(8), for an agent by Eq(9), and for water by Eq(10):

$$\dot{m}_{3,1} = \dot{m}_{5,1} \tag{8}$$

$$\dot{m}_{3,2} = \dot{m}_{5,2} \tag{9}$$

$$\dot{m}_{3,3} = \dot{m}_{4,3} + \dot{m}_{5,3} \tag{10}$$

Mass balance of components in the separation unit 2 is calculated for biomass by Eq(11), for an agent by Eq(12), and for water by Eq(13):

$$\dot{m}_{5,1} = \dot{m}_{7,1} \tag{11}$$

$$\dot{m}_{5,2} = \dot{m}_{7,2} \tag{12}$$

$$\dot{m}_{5,3} = \dot{m}_{6,3} + \dot{m}_{7,3} \tag{13}$$

The total mass flow rates of streams 1 and 2 are expressed by Eq(14) and Eq(15), respectively,

$$\dot{m}_{1,1} + \dot{m}_{1,3} = F \tag{14}$$

$$\dot{m}_{2,2} + \dot{m}_{2,3} = A \tag{15}$$

where F is the separation line performance (kg h^{-1}) and A is the mass flow rate of the aqueous solution including the added agent (kg h^{-1}). The feed mass flow rate of the biomass is expressed by Eq(16), where $C_{1,1}$ is the mass fraction of the biomass in the microalgal suspension feed. The mass flow rate of the dosed coagulant/flocculant is described by Eq(17), where $C_{2,2}$ is the mass fraction of the agent in the aqueous solution including a coagulant/flocculant.

$$\dot{m}_{1,1} = C_{1,1} \cdot \dot{m}_{1,3} \tag{16}$$

$$\dot{m}_{2,2} = C_{2,2} \cdot \dot{m}_{2,3} \tag{17}$$

The impact of separation processes on the water outflow in the microalgal suspension is described by Eq(18) for Separation 1, and by Eq(19) for Separation 2:

$$\dot{m}_{5,3} = \left(1 - \frac{\eta_1}{100}\right) \cdot \dot{m}_{3,3} \tag{18}$$

$$\dot{m}_{7,3} = \left(1 - \frac{\eta_2}{100}\right) \cdot \dot{m}_{5,3} \tag{19}$$

where η_1 is the efficiency of Separation 1 (%) and η_2 is the efficiency of Separation 2 (%). The output volume concentration of the microalgal suspension c_F (g L^{-1}) is calculated according to the following equation Eq(20):

$$c_F = \frac{\dot{m}_{7,1}}{\dot{V}_{SUSP}} \tag{20}$$

where V_{SUSP} (m^3 h^{-1}) is the volumetric flow rate of the microalgal suspension after the separation process, $\dot{m}_{7,1}$ (kg h^{-1}) is the mass flow rate of the biomass in the stream 7. In this case, the weight of 1 L of the microalgal suspension equal to 1 kg was assumed.

4. Results: mass balance and energy consumption

The results of the following cases were calculated assuming the separation line capacity of 50 m^3 h^{-1}. The various separation technologies differ in separation efficiency. For example, the separation efficiency of flotation is low if no agents are applied before the separation. In this case, the efficiency tends to be in the range from 50 to 60 %. If the membrane separation is applied, the harvesting efficiency of 70 % can be reached. Unlike this, the centrifugation enables to reach the harvesting efficiency of 90 %.

In Case I, the effect of configuration and stage efficiency on the outflow stream flow rate and outflow microalgal concentration is demonstrated in Table 3 for the input concentration of the microalgal suspension = 5 g L^{-1}. The following parameters such as the final volumetric flow rates in each stage V_{SUSP1} and V_{SUSP2} (m^3 h^{-1}), and the final concentrations in each stage c_{F1}, c_{F2} of the microalgal suspension (g_{mic} L^{-1}) are shown. In the next cases,

the separation efficiency of 80 % was assumed for the stage Separation 1 (e.g., a membrane technology), and 90 % was assumed for the stage Separation 2 (e.g., centrifugation), and the coagulation/flocculation was used as a pretreatment method. The results are presented in Table 4 for the input concentration of the microalgal suspension of 1 g L^{-1}(Case II), and in Table 5 for the input concentration of the microalgal suspension of 5 gL^{-1} (Case III).

Table 3: Case I: the effect of configuration and stage efficiency on outflow stream flowrate and outflow microalgal concentration for the input concentration of the microalgal suspension = 5 g L^{-1} and the separation line capacity = 50 m^3 h^{-1}

Separation 1 (%)	Separation 2 (%)	V_{SUSP1} (m^3 h^{-1})	c_{F1} (g_{mic} L^{-1})	V_{SUSP2} (m^3 h^{-1})	c_{F2} (g_{mic} L^{-1})
50	80	25.124	9.9	5.224	47.6
50	90	25.124	9.9	2.736	90.1
60	80	20.149	12.4	4.229	58.8
60	90	20.149	12.4	2.239	111.1
70	80	15.174	16.4	3.234	76.9
70	90	15.174	16.4	1.741	142.9

Table 4: Case II: A two-step process with a pretreatment by coagulation or flocculation for the input concentration of the microalgal suspension = 1 g L^{-1} and separation line capacity = 50 m^3 h^{-1}

Microalgae	Coagulant/Flocculant (CF)	CF dosage ($g_{C/F}$ L^{-1})	V_{SUSP1} (m^3 h^{-1})	c_{F1} (g_{mic} L^{-1})	V_{SUSP2} (m^3 h^{-1})	c_{F2} (g_{mic} L^{-1})
Chlamydomonas sp.	cationic guar gum	0.1	11.169	4.5	1.166	42.8
Chlorella sp.	cationic locust bean gum	0.055	10.459	4.8	1.093	45.7
Chlorella vulgaris	poly γ-glutamic acid	0.02	10.207	4.9	1.066	46.8
Chlorella protothecoides	poly γ-glutamic acid	0.02	10.207	4.9	1.066	46.8
Micractinium sp.	cationic locust bean gum	0.04	10.507	4.8	1.098	45.5
Scenedesmus sp.	$Al_2(SO_4)_3$	0.1	11.901	4.2	1.243	40.2
Scenedesmus sp.	$Ca(OH)_2$	0.4	17.397	2.9	1.827	27.3
Scenedesmus sp.	$FeCl_3$	0.15	12.831	3.9	1.341	37.3

Note: CF dosages were overtaken from Hladíková and Šulc (2021).

Table 5: Case III: A two-step process with a pretreatment by coagulation or flocculation for the input concentration of the microalgal suspension = 5 g L^{-1} and separation line capacity = 50 m^3 h^{-1}

Microalgae	Coagulant/Flocculant (CF)	CF dosage ($g_{C/F}$ L^{-1})	V_{SUSP1} (m^3 h^{-1})	c_{F1} (g_{mic} L^{-1})	V_{SUSP2} (m^3 h^{-1})	c_{F2} (g_{mic} L^{-1})
Chlamydomonas sp.	cationic guar gum	0.1	15.845	15.7	1.834	135.7
Chlorella sp.	cationic locust bean gum	0.055	12.293	20.2	1.463	170.1
Chlorella vulgaris	poly γ-glutamic acid	0.02	11.037	22.5	1.331	186.9
Chlorella protothecoides	poly γ-glutamic acid	0.02	11.037	22.5	1.331	186.9
Micractinium sp.	cationic locust bean gum	0.04	12.536	19.8	1.488	167.2
Scenedesmus sp.	$Al_2(SO_4)_3$	0.1	19.505	12.8	2.216	112.3
Scenedesmus sp.	$Ca(OH)_2$	0.4	47.421	5.3	5.133	48.5
Scenedesmus sp.	$FeCl_3$	0.15	24.157	10.3	2.702	92.1

Table 6: Case III: A two-step process with a pretreatment by coagulation or flocculation for the input concentration of the microalgal suspension = 5 g L^{-1} and separation line capacity = 50 m^3 h^{-1}

Microalgae	Coagulant/Flocculant	Energy requirement (kWh m^{-3})
Chlamydomonas sp.	cationic guar gum	11.7
Chlorella sp.	cationic locust bean gum	10.9
Chlorella vulgaris	poly γ-glutamic acid	10.6
Chlorella protothecoides	poly γ-glutamic acid	10.6
Micractinium sp.	cationic locust bean gum	10.9
Scenedesmus sp.	$Al_2(SO_4)_3$	12.6
Scenedesmus sp.	$Ca(OH)_2$	12.1
Scenedesmus sp.	$FeCl_3$	13.7

Finally, the energy demand of the harvesting process was estimated for Case III, see Table 6. For this purpose, the following energy demands were adopted: i) the energy demand of coagulation/flocculation of 0.07 kWh m^{-3} of the microalgal suspension including the mixture of an agent and water (Danquah et al., 2009), ii) the energy consumption of 2.9 kWh m^{-3} of permeate (Zhao et al., 2020) for membrane separation by a PVDF membrane (stage Separation 1), and iii) the energy demand of 8 kWh m^{-3} of the input microalgal suspension (Danquah et al., 2009) for centrifugation (stage Separation 2). The energy required for pumping between units was neglected. Considering the equivalent length of 100 m, the velocity of 1.5 m s^{-1}, and the pumping efficiency of 85 %, the estimated pumping energy is 0.027 kWh m^{-3}. The energy consumption is in the range of 10.6 to 13.7 kWh m^{-3} of the microalgal suspension feed, i.e., 2 ÷ 2.7 kWh kg^{-1} of algal feed. Compared to Fasaei et al. (2018), the higher energy demand was estimated under the given assumptions.

5. Conclusions

A spreadsheet-based tool for modelling of one- or two-step harvesting process was presented. The harvesting technology can be configured as a single-stage or two-stage process. The used separation processes are defined by a user. Optionally, a pretreatment by coagulation or flocculation before the separation process can be also included. In this case, it is important to consider the added volume of water because a coagulant and flocculant are dosed as an aqueous solution. The tool enables to provide parameters for the equipment basic design. These parameters are the mass flow rates of individual media, an agent consumption, and the estimation of energy consumption. The applicability of this approach was demonstrated on three cases considering some simplifying assumptions. The more accurate are the input data and the process model, the more accurate results can be obtained. For future research, the database implemented in the model will be further extended.

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