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# Harvesting economics and strategies using centrifugation for cost effective separation of microalgae cells for biodiesel applications

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## HIGHLIGHTS

- ▶ A new strategy for minimizing microalgal harvesting costs was developed.
- ▶ Lower harvesting efficiencies with higher flow rates were more cost effective.
- ▶ Centrifugation can potentially be a primary harvesting technique.
- ▶ Energy consumption and costs for various algal densities and lipids are provided.

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ABSTRACT

Inefficient or energy-intensive microalgal harvesting strategies for biodiesel production have been a major setback in the microalgae industry. Harvesting by centrifugation is generally characterized by high capture efficiency (>90%) under low flow rates and high energy consumption. However, results from the present study demonstrated that by increasing the flow rates (>1 L/min), the lower capture efficiencies (<90%) can be offset by the larger volumes of culture water processed through the centrifuge, resulting in net lower energy consumption. Energy consumption was reduced by 82% when only 28.5% of the incoming algal biomass was harvested at a rate of 18 L/min by centrifugation. Harvesting algal species with a high lipid content and high culture density could see harvesting costs of $0.864/L oil using the low efficiency/high flow rate centrifugation strategy as opposed to $4.52/L oil using numbers provided by the Department of Energy for centrifugation harvesting.



## 1. Introduction

Algae are a potentially viable and competitive fuel crop because of their high per-acre productivity, absence of competition with feed/food-based products, use of otherwise non-productive, non-arable land, utilization of a wide variety of water sources (fresh, brackish, saline, and wastewater), mitigation of greenhouse gases released into the atmosphere, and production of both biofuels and valuable co-products (Pienkos and Darzins, 2009). With some species containing lipid contents as high as 70% of the cell's biomass, microalgae could potentially produce nearly 136,900 L/ha of biodiesel per year as compared to soybean which is capable of only 446 L/ha (47 gal/ac) per year (Chisti, 2007); however, trials under ideal conditions have shown that fast-growing microalgae can only yield 16,828–18,168 L/ha/year (1800–2000 gal/ac/year) (Um and Kim, 2009).

Given the relatively low biomass concentration obtainable in microalgal cultivation systems, marginal density difference with culture water (average ~1020 kg/m$^3$), and the small size of microalgal cells (5–50 μm in diameter), costs and energy consumption for biomass harvesting are significant concerns that needs to be addressed properly (Li et al., 2008; Pieterse and Cloot, 1997). Depending on species, cell density, and culture conditions, harvesting algal biomass has been estimated to contribute 20–30% to the production cost (Gudin and Thepenier, 1986).

Such cost estimates are typically associated with the dewatering of microalgae through centrifugation. Continuous flow centrifuge systems allow sediment-bearing water to be pumped continuously through the bowl assembly, forcing particles to the wall while clarified water passes through the overflow (Rees et al., 1991). Quick dewatering of algae is evident with 84% removal efficiency of 0.2 g/L algal culture at a flow of 100 gal/min (379 L/min) under a rotational velocity of 3000 rpm (Kothandaraman and Evans, 1972). Unfortunately, under these conditions the use of centrifuges for algal separation is very energy intensive. The use of centrifugation for harvesting algae cultures from 0.04% to 4% dry

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weight on average costs 1.3 kW h/$m^3$ of pond water (Sim et al., 1988). To make the drying process more effective, the processed algal biomass must be increased to at least 20% dry weight during the dewatering stage (Putt, 2007). Increasing the concentration to 22% dry algal biomass can utilize 8 kW h/$m^3$ (Mohn, 1980). Therefore, centrifugation may be feasible for high-value products, but is far too costly in an integrated system producing lower-value products, such as algal oils for biofuel production (Pienkos and Darzins, 2009). Techniques such as membrane filtration, which are capable of consuming as little as 0.25 kW h/$m^3$ at 70% harvest efficiency, would appear to be more suitable for harvesting algae for biodiesel application (Bilad et al., 2012); however, regular binding of the filters, head loss, and back flushing create challenges as a primary harvesting process. Additionally, the harvested product from membrane filters may be too dilute for lipid extraction and may need additional concentration. In order to determine under which conditions centrifugation can be competitive with harvesting techniques such as coagulation/flocculation, filtration, and flotation, an economic model for harvesting by centrifugation was developed and an optimum harvesting strategy was proposed.

## 2. Methods

*Nannochloris* sp., a unicellular green alga, was cultivated outdoors in a 122 cm D × 91 cm H fiberglass tank filled with approximately 979 L of F/2 medium. The culture was circulated for nearly two weeks using an air lift pump which facilitated gas transfer ($CO_2$, $O_2$, and degassing) and brought lower-dwelling cells to the surface for sunlight exposure. This approach allowed the algae to reach a culture density of approximately 100 mg-dry/L. For each run, a portion of the culture was transferred to a 55-L secondary sump for easier access before being pumped to the nearby centrifuge.

The 1.5-HP (1.12 kW) continuous-flow centrifuge from US Filter-Maxx (3000*g* centrifuge) was allowed to run non-stop throughout the testing. Culture from the secondary sump was drawn by a rotary vane pump (Procon 115B330F31XX) connected to the 0.635-cm National Pipe Thread (NPT) stem on top of the centrifuge bowl. Flow rates varied from 0.94 to 23.2 L/min using the flow regulator attached on the suction side of the pump. The effluent leaving the 3.81-cm NPT outlet was allowed to drain to the ground (Fig. 1).

The centrifuge was switched on and allowed to reach its maximum speed before the algae inflow was initiated. The start-up normally took between 5 and 10 s. When the inflow was initially applied, the centrifuge was operated for 10 min before the first effluent sample was collected. After collecting the first sample, samples were collected at 1-min intervals. When the flow rate was varied, an additional 10 min was allowed to return the system to new steady-state conditions. The effluent samples were compared to the initial culture density which was randomly sampled from the 55-L secondary sump throughout the entire testing. Samples were compared by absorbance measurements with a spectrophotometer operating at 680 nm. The absorbance values were correlated to the total suspended solids (TSS determined in triplicate for each data point).

## 3. Results and discussion

Generally, centrifuges are considered to be too energy intensive to be suitable for microalgae harvesting for biodiesel production. For most applications, centrifuges are adjusted primarily to maximize capture efficiency. However, cost-effective harvesting of algal cells may or may not coincide with the highest capture efficiency. At higher flow rates (>1 L/min), the lower capture efficiencies will be offset by the larger volumes of culture processed through the centrifuge. Due to the microscopic size of the cells, longer retention times within the centrifuge bowl are required for their sedimentation. As anticipated, results indicated that longer retention times (slower flow rates) correlated with more energy being directed to a smaller volume of culture per min (Fig. 2).

The harvesting efficiency was determined by calculating the percentage of biomass removed from the influent culture solution. The cell removal efficiency for the centrifuge reached 94% (±0.24%) when an incoming flow rate of 0.94 L/min was applied. However, to collect biomass at these high capture efficiencies, an energy input of nearly 20 kW h/$m^3$ (of culture water) was required to harvest the cells. As the incoming flow increased, the amount of energy per cubic meter decreased, but the harvested mass also decreased. Only 17% (±1.57%) of the incoming biomass was harvested when the flow rate was increased to 23 L/min; however, at this rate only 0.80 kW h/$m^3$ of energy was required to harvest the biomass. The full effect of the harvesting efficiency in relation to energy consumption and flow rate cannot be realized unless a final cost on algal oil is plotted (Fig. 3).

The algal oil density was assumed to be 864 g/L, which falls within the range determined by Kumar et al. (2011) for various species (857–892 g/L). At 100 mg/L culture density, 26% lipid concentration, and $0.09 per kW h electricity cost, the cost of harvesting algal cells for an equivalent 1 L of algal oil was determined from the energy ($y$) consumed at various flow rates and the corresponding capture efficiencies ($x$).

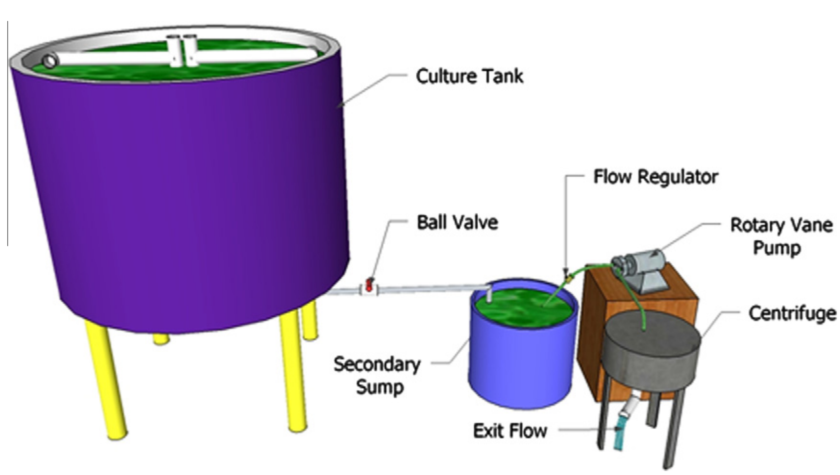


**Fig. 1.** Experimental setup for centrifugation testing. The primary culture was diverted to a secondary sump, from where it was pumped through the centrifuge (one-pass). The cell capture efficiency was computed based on algal densities in the influent and the water exiting from the centrifuge.