Improved Algal Harvesting Using Suspended Air Flotation

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ABSTRACT: Current methods to remove algae from a liquid medium are energy intensive and expensive. This study characterized algae contained within a wastewater oxidation pond and sought to identify a more efficient harvesting technique. Analysis of oxidation pond wastewater revealed that algae, consisting primarily of *Chlorella* and *Scenedesmus*, composed approximately 80% of the solids inventory during the study period. Results demonstrated that suspended air flotation (SAF) could harvest algae with a lower air:solids (A/S) ratio, lower energy requirements, and higher loading rates compared to dissolved air flotation (DAF) ($P < 0.001$). Identification of a more efficient algal harvesting system may benefit wastewater treatment plants by enabling cost effective means to reduce solids content of the final effluent. Furthermore, use of SAF to harvest commercially grown *Chlorella* and *Scenedesmus* may reduce manufacturing costs of algal-based products such as fuel, fertilizer, and fish food. *Water Environ. Res.,* **81,** 702 (2009).

KEYWORDS: Suspended air flotation (SAF), dissolved air flotation (DAF), wastewater, algae, *Chlorella*, *Scenedesmus*, air:solids (A/S) ratio.

Introduction

Wastewater treatment ponds are systems that effectively stabilize wastewater by reducing biochemical oxygen demand (BOD) (Hammouda et al., 1995). Use of wastewater ponds is widespread because they are economical, reliable, and simple to operate (Bahlaoui et al., 1997; Oswald, 1990). Lower operating costs of pond systems relative to conventional treatment systems, such as activated sludge, are partially attributed to natural aeration provided by photosynthesizing algae (Craggs et al., 1997; Green et al., 1995; Hammouda et al., 1995; Hosetti and Frost, 1995; Oswald et al., 1978).

Although algae effectively can treat wastewater, their dominance in wastewater oxidation pond ecosystems can cause high levels of total suspended solids (TSS) in the final effluent (Bich et al., 1998; Craggs et al., 1997). Excessive algal accumulation in wastewater effluent may prevent treatment facilities from meeting TSS standards outlined in Federal Water Pollution Control Amendments (Naghavi and Malone, 1986).

Craggs et al. (1997) noted that although several harvesting options exist, incompatibilities between efficiency and cost-effectiveness have restricted their application. The goals of this study were to identify major algal assemblages in a wastewater oxidation pond system and to identify a more efficient, cost-effective algal harvesting technique. This study compared the ability of dissolved air flotation (DAF) and suspended air flotation to remove algae from wastewater ponds.

Algae common to wastewater pond systems such as *Chlorella* (3 to 15 μm) and *Scenedesmus* (30 μm) are difficult and costly to remove from wastewater because of their small size and low specific gravity (Craggs et al., 1997; Oswald et al., 1978; Bare et al., 1975). Algae are poorly compacted by gravity because of negative surface charges and dilute concentrations within the liquid medium (Teixeira and Rosa, 2006; Mulaku and Nyanchaga, 2004; Koopman and Lincoln, 1983; Folkman, 1970). These characteristics make sedimentation unsuitable for efficient algae harvesting. In contrast, DAF has proven to remove efficiently small suspended particles from liquid (Bourgeois et al., 2004; Chung et al., 2000; French et al., 2000; Bunker et al., 1995). Green et al. (1995) recognized DAF as the most efficient and cost-effective method to harvest algae from wastewater.

The DAF units use a compressor to supersaturate flotation water with air in a saturator (de Rijk et al., 1994). The flotation water is then released into a flotation cell at atmospheric pressure, causing air to precipitate as small bubbles from the solution (Lundh et al., 2000; de Rijk et al., 1994). Bubbles adhere to the algal conglomerates and cause them to float to the surface, where excess liquid drains through the accumulating algal mat (Féris and Rubio, 1999; de Rijk et al., 1994; Koopman and Lincoln, 1983). Although effective, these DAF units are relatively expensive to operate because they involve energy-intensive air compression to approximately 390 kPa (56 psig) (Féris and Rubio, 1999; Haarhoff and Steinbach, 1996).

The SAF is similar to DAF relative to creating small bubbles that adhere to algal cells, forcing them to the surface of the water. However, SAF units create small bubbles with surfactants, eliminating the need for a compressor and saturator. These characteristics make SAF a promising technology for algal harvesting because they have fewer mechanical components, require less space, and use less energy than many DAF units.

During this study, quantities of algae contained within an oxidation pond at the Arcata Wastewater Treatment Plant, Arcata, California, were estimated. Performance parameters used to compare DAF and SAF were air:solids (A/S) ratio, solids loading rate, hydraulic loading rate, percent solids capture, total solids concentration of thickened algal biomass, and energy consumption.

Materials and Methods

Study Site and Algal Supply. Samples were collected from the initial oxidation pond at the Arcata plant because it contained the greatest concentration of algae. Algal biomass supply was determined using chlorophyll *a* analysis, which required the extraction of chlorophyll from a filtered sample using an acetone solution. Samples were acidified with a 0.1 N solution of hydrochloric acid to

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account for interferences caused by the presence of pheophytin. Absorbance of the extract was measured with a spectrophotometer and used to determine algal concentration. Chlorophyll *a* extraction procedures and biomass determination followed those outlined in section 10200H of Standard Methods (APHA, 1998).

Supply of algae within the pond was compared with the TSS concentration of the wastewater samples. This comparison determined the percentage of the solids inventory consisting of algae. The total suspended solids concentrations were determined using procedure 2540D of Standard Methods (APHA, 1998). Relative abundance of *Chlorella* within the algal biomass was estimated by dividing the number of *Chlorella* cells by the total number of organisms within a hemocytometer grid.

Algal Harvesting Procedures. The DAF and SAF technologies were used to concentrate algae from wastewater. Harvesting of algae from wastewater samples occurred within 72 hours of sample collection. To maximize efficiency of both flotation technologies, the addition of a coagulant was necessary to destabilize suspended algal cells. To achieve this, an aliquot of 0.5 mL of 1% (by mass) C-FLOC 60 cationic polymer solution was added per 100 mL of wastewater. Three different ratios of wastewater to flotation water were used for both technologies. Thirty trials were performed for each ratio to ensure normal distribution of data.

A bench-scale DAF unit was used to concentrate algae from wastewater. Ratios of wastewater to flotation water were 3:1, 2:1, and 1:1 (corresponding recycle ratios of 25%, 33%, and 50%, respectively), where the total volume of each ratio equaled 1.2 L. To prepare the flotation water, the DAF saturator was filled with 3 L of tap water and pressurized at 450 kPa (65 psi) for 10 minutes with a small compressor. The flotation water in the pressurization vessel was released into a flotation cell (8.9 cm diameter × 21 cm height) containing flocculated wastewater sample. Rise time necessary for solids to reach the surface of the flotation vessel was determined by visual observation and timed with a stopwatch. The resulting algal mat was given an additional three minutes to drain before being skimmed from the surface.

A bench-scale SAF unit (Heron Innovators, Roseville, California) also was used to concentrate algae from wastewater. Ratios of wastewater to flotation water used were 160:1, 120:1, and 80:1, where total volume of each ratio equaled 1.2 L. The SAF mixing vessel was filled with 2 L of tap water and 5 mL of Heron MicroFroth™ cationic surfactant. A 10.6-Lpm (2.8 gpm), direct-current SHURflo diaphragm pump, model 2088-422-444 (SHURflo, Cyprus, California), mixed the surfactant and tap water within the SAF mixing vessel. The surfactant and tap water were considered well mixed when the pressure within the SAF mixing vessel was reduced from 210 kPa (30 psi) to 100 kPA (15 psi). With the diaphragm pump running, a discharge valve was opened, allowing the flotation water to be pumped into a 50-mL graduated cylinder. The volume of flotation water needed for each ratio was removed from the graduated cylinder with a pipette and released into the flotation vessel (8.9 cm diameter × 21 cm height) containing the flocculated wastewater sample. The rise time necessary for solids to reach the surface of the flotation vessel was timed with a stopwatch. The resulting algal mat was given an additional three minutes to drain before being skimmed from the surface.

Performance of DAF and SAF thickening technologies were compared to determine which technology was most suitable for the removal of algae from wastewater. The A/S ratio, percent solids capture, solids loading rate, hydraulic loading rate, total solids

Table 1—Properties of air used to calculate air:solids ratio (A/S ratio) of dissolved air flotation (DAF) and suspended air flotation (SAF).

	Argon	Nitrogen	Oxygen
Henry's constant	26.9	63.3	31.6
Molar fraction in air	0.0098	0.7807	0.2095
Molarity (g/mol)	39.9	28.0	32.0

content of thickened algae, and energy requirements were used to evaluate the two technologies.

Air:Solids Ratio. The A/S ratio is an operational parameter used to assess performance of flotation technologies (Viessman and Hammer, 2005). It is useful to process a sample of certain solids content when determining the quantity of air required. For this experiment, the A/S ratio was reported in units of milligrams of air per milligrams of solids. Properties of air used to calculate A/S ratio are listed in Table 1 (Haarhoff and Steinbach, 1996).

Atmospheric air is composed of nitrogen, oxygen, and argon (Haarhoff and Steinbach, 1996). The quantity of these gases contained within flotation water following pressurization in a DAF saturator must be determined to calculate the A/S ratio. Haarhoff and Steinbach (1996) determined this quantity with Henry's Law (Equation 1).

$$G_i = H_i \cdot C_i \qquad (1)$$

Where,

G_i = Mass concentration of i in air (g/m^3);
H_i = Henry's Constant for i; and
C_i = Mass concentration of i in water (g/m^3).

Solving this equation required the Henry's constant for each gas, and its mass concentration within air under variable pressure. Given that 1 m^3 of dry air contains 44.6 moles at 0°C at a pressure of 101.3 kPa, Haarhoff and Steinbach (1996) defined mass concentration of any gas in air as (Equation 2):

$$G_i = y_i \cdot M_i \cdot 44.6 \cdot \left(\frac{273.15}{T}\right) \cdot \left(\frac{P_{tot}}{101.3}\right) \qquad (2)$$

Where,

G_i = Mass concentration of i in air (g/m^3);
y_i = Molar fraction of i in air (g/m^3);
M_i = Molecular weight of i (g/mol);
T = Temperature (K); and
P_{tot} = Pressure (kPa).

Suspended air flotation is a process that generates microbubbles chemically rather than physically. Because of this, the A/S ratio cannot be calculated using Henry's Law. Instead, the volume of air contained within flotation water was determined by visual observation. This was achieved by pumping 100 mL of flotation water directly into a graduated cylinder. The volume of liquid remaining in the graduated cylinder when bubbles were no longer visible was subtracted from the initial volume of 100 mL. This difference represented the fraction of flotation water composed of air. The mass of air contained within the volume of flotation water was then determined by calculating the density of air at 293.15 K (20°C) (Equation 3).

Table 2—Air:solids ratio (A/S ratio), solids loading, and quantities of air (mass and volume) contained within flotation water of dissolved air flotation (DAF) and suspended air flotation (SAF) at various operating ratios.

Treatment	mg of air	mL of air	mg of solids	mg/L feed	A/S ratio
DAF 3:1	32	26	122	136	0.26
DAF 2:1	42	35	123	154	0.34
DAF 1:1	63	52	72	120	0.88
SAF 160:1	9.0	7.5	149	124	0.06
SAF 120:1	12	10	184	153	0.07
SAF 80:1	18	15	172	143	0.10

$$D = \frac{M}{V} \tag{3}$$

Where,

D = Density (g/L);
M = Molarity (g/mol); and
V = Volume (L/mol).

Where molarity of air was determined with Equation 4, and volume of air at 101.3 kPa (1 atm) and 293.15 K (20°C) was calculated using the ideal gas law (Equation 5).

$$M_{air} = (M_{O_2} \cdot MW_{O_2}) + (M_{N_2} \cdot MW_{N_2}) + (M_{Ar} \cdot MW_{Ar}) \tag{4}$$

$$V = \frac{nRT}{P} \tag{5}$$

Where,

M_{air} = Molarity of air (g/mol);
MO_2 = Molar fraction of air comprised of oxygen;
MWO_2 = Molarity of oxygen (g/mol);
MN_2 = Molar fraction of air comprised of nitrogen;
MWN_2 = Molarity of nitrogen (g/mol);
M_{Ar} = Molar fraction of air comprised of argon;
MW_{Ar} = Molarity of argon (g/mol);
n = Moles of air;
R = Ideal gas constant (0.0821 L-atm/mol-K); and
P = Pressure (atm).

Percent Capture. Percent capture measures how efficiently solids are removed from a liquid sample. Percent capture for DAF and SAF were calculated using initial solids content and solids concentration of the subnatant following flotation (Equation 6).

$$PC = \frac{TSS_i - TSS_f}{TSS_i}(100) \tag{6}$$

Where,

PC = Percent capture (percent);
TSS_i = Initial total suspended solids content (mg/L); and
TSS_f = Subnatant total suspended solids content (mg/L).

The TSS values of samples concentrated were determined in accordance with section 2540D of Standard Methods (APHA, 1998). Initial TSS values for DAF were diluted with distilled water to compensate for effects caused by the introduction of flotation water. Dilutions were not performed on raw samples used for SAF because effects incurred by the introduction of the flotation water accounted for less than 1% of the total sample volume and were assumed to be negligible. Subnatant removal after flotation treatment was performed with a 100-mL volumetric pipette.

Hydraulic and Solids Loading Rates. Hydraulic and solids loading rates determine the feed rate that will optimize percent solids capture. Excessive solids or hydraulic loading will reduce the ability of flotation technologies to adequately remove solids. Sample volume, TSS content, flotation cell surface area, and rise time were used to determine solids loading rate (Equation 7) and hydraulic loading rate (Equation 8) for DAF and SAF.

$$SLR = \frac{(TSS \cdot S)}{(RT)} \cdot \frac{1}{SA} \tag{7}$$

$$HLR = \frac{S}{(RT)} \cdot \frac{1}{SA} \tag{8}$$

Where,

SLR = Solids loading rate (g/min/m^2);
TSS = Total suspended solids content (g/L);
S = Volume of sample (L);
RT = Rise time (min);
SA = Flotation cell surface area (m^2); and
HLR = Hydraulic loading rate (L/min/m^2).

Total Solids Concentration. Concentration of algal biomass with flotation technology reduces volume by separating the algal cells from the liquid medium. Concentrated algal slurry is desirable because it improves the efficiency of future processing and makes handling less complicated. Total solids analysis was performed on algae skimmed from the surface of the flotation cell. The harvested algae was placed in an aluminum sample dish and dried between 103 to 105°C for 24 hours. Solids concentration was determined by

Table 3—Results from one-way analysis of variance (ANOVA) and Fisher's multiple comparison test evaluating mean total solids concentration, percent capture, solids loading rate, and hydraulic loading rate for dissolved air flotation (DAF) at three operating ratios [SE = standard error, n = sample size, mean = average value for each operational parameter, and P = level of statistical significance (α = 0.05)].

Variable	1:1 ratio		2:1 ratio		3:1 ratio		n	P
	Mean	SE	Mean	SE	Mean	SE		
Total solids concentration (%)	5.0	0.05	4.5	0.05	4.8	0.04	30	<0.001
Percent capture (%)	83.7[a]	0.85	84.9[a]	0.81	78.3	0.97	30	<0.001
Solids loading rate (g/min/m^2)	14.1	0.17	29.4	0.45	22.7	0.27	30	<0.001
Hydraulic loading rate (L/min/m^2)	221	2.6	267	4.1	247	2.9	30	<0.001

[a] Means did not differ ($P < 0.05$) based on a Fisher's multiple comparison test.

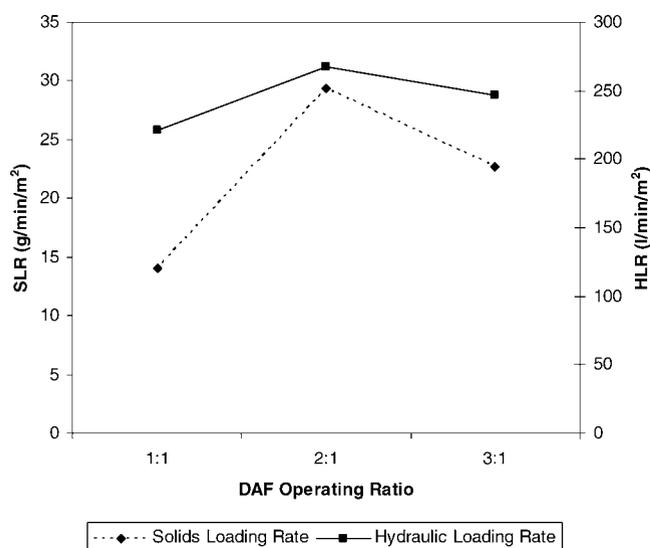**Figure 1—Relationship between solids and hydraulic loading rates with different dissolved air flotation (DAF) operating ratios (air:solids ratio).**
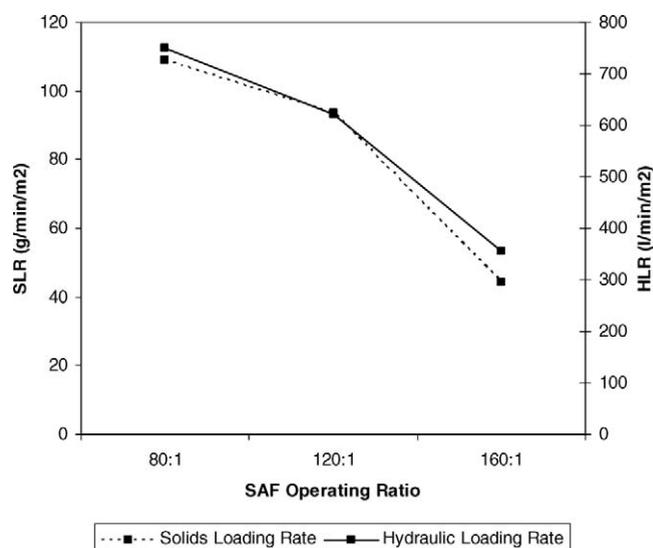

Figure 2—Relationship between solids and hydraulic loading rates with different suspended air flotation (SAF) operating ratios (air:solids ratio).

subtracting the tare weight of the sample dish from the weight of the dish containing the dry sample (Equation 5). Procedures to determine total solids followed those outlined in section 2540B of Standard Methods (APHA, 1998).

$$TS = \frac{Wt_3 - Wt_1}{Wt_2 - Wt_1}(100) \qquad (9)$$

Where,

  TS = Total solids (percent dry);
  Wt_1 = Dish tare weight (g);
  Wt_2 = Dish and wet sample weight (g); and
  Wt_3 = Dish and dry sample weight (grams).

Energy Requirements. Energy requirements for both technologies were compared. Power (watts) consumed by SAF was estimated by multiplying direct current (DC) amperage and voltage consumed by the diaphragm pump. Voltage was determined with a Fluke model 83 III multimeter (Fluke Corporation, Everett, Washington) and amperage was measured with an Extech model 380942 ammeter (Extech Instruments, Waltham, Massachusetts). Alternating current (AC) power (watts) consumed by the air compressor used in DAF was determined with a Brand Electronics model 21-1850CI digital power meter (Brand Electronics, White-field, Maine). Electrical energy consumed per liter of sample treated for SAF and DAF was determined (Equation 10).

$$E = \frac{W \cdot H}{S_t} \qquad (10)$$

Where,

  E = Total energy consumed (Wh/L of sample);
  W = Power consumed to prepare flotation water (W);
  H = Equipment runtime to prepare flotation water (hours); and
  S_t = Sample treated (L).

Statistical Analysis. One-way analysis of variance (ANOVA) of mean solids loading rate, hydraulic loading rate, total solids, and percent capture was performed for all ratios used by DAF and SAF. Fisher's multiple comparison test was used if statistically significant differences between more than two means were observed. Two-sample t-tests were used in cases where only two means were compared. Results from the statistical analysis identified the operating ratio providing most efficient operation. The ratio providing maximum performance served as a basis for comparison between DAF and SAF. All statistical analyses were conducted with MINITAB 14 Statistical Package (Minitab Inc., State College, Pennsylvania) for Windows.

Results and Discussion

Algal Supply. Samples collected from the discharge of the initial oxidation pond at the Arcata wastewater treatment facility between June and October 2006 were used to estimate algal supply. Results from chlorophyll a estimated the average algal supply within the pond to be 104 ± 5.0 mg/L (n = 19). The TSS concentration was 131 ± 3.3 mg/L (n = 27), indicating that approximately 80% of the solids inventory within the oxidation pond comprised algal biomass. Results from hemocytometer analysis estimated that *Chlorella* composed an average of $62.1\% \pm 4.2\%$ of the total organisms observed (n = 17). The majority of remaining organisms consisted of *Scenedesmus*, although their relative abundance was not determined. However, it is important to note that environmental factors such as temperature and available light govern algal growth rates, making it unlikely that algal supply within the oxidation pond would remain static throughout seasonal variation (Sansawa and Endo, 2004; Mayo and Noike, 1996).

Algae Removal with Dissolved Air Flotation. The DAF operating ratios of 3:1, 2:1, and 1:1 (recycle ratios of 25%, 33%, and 50%, respectively) were used to remove algae from wastewater. Solids loading and mass of air released from the flotation water upon introduction into the flotation cell were used to determine the A/S ratio. Increasing volumes of flotation water used by DAF increased

Table 4—Results from one-way analysis of variance (ANOVA) and Fisher's multiple comparison test evaluating mean total solids concentration, percent capture, solids loading rate, and hydraulic loading rate for suspended air flotation (SAF) at three operating ratios [SE = standard error, n = sample size, mean = average value for each operational parameter, and P = level of statistical significance (α = 0.05)].

Variable	80:1 ratio		120:1 ratio		160:1 ratio		n	P
	Mean	SE	Mean	SE	Mean	SE		
Total solids concentration (%)	4.7[a]	0.04	4.8[a]	0.07	4.7[a]	0.04	30	0.111
Percent capture (%)	63.3	1.2	76.6	0.74	70.1	1.1	30	<0.001
Solids loading rate (g/min/m^2)	109	2.9	93.7	1.7	44.3	0.82	30	<0.001
Hydraulic loading rate (L/min/m^2)	750	20.3	620	11.5	355	6.6	30	<0.001

[a] Means did not differ ($P < 0.05$) based on a Fisher's multiple comparison test.

the mass of air, but reduced the amount of sample that could be processed per batch. As a result, A/S ratios for 1:1, 2:1, and 3:1 operating ratios were 0.88, 0.34, and 0.26, respectively (Table 2).

Although a higher A/S ratio resulting from greater proportions of flotation water decreased the amount of time needed to float a sample, it did not necessarily maximize solids and hydraulic loading rates. Most efficient solids and hydraulic loading rates occur when ideal proportions of flotation water and sample exist. During this study, it was discovered that DAF operating at a 2:1 ratio had a significantly higher hydraulic loading rate and solids loading rate when compared with operating ratios of 1:1 and 3:1 ($P < 0.001$) (Table 3). The explanation for this is that the 1:1 ratio had too much flotation water and not enough sample; while the 3:1 ratio contained too much sample and not enough flotation water. This demonstrates the importance of having the correct A/S ratio (i.e., correct proportions of flotation water and sample) to ensure efficient operation (Figure 1).

Percent capture measures how effectively solids are removed from the sample, although total solids analysis describes the concentration of the harvested solids. Results from a one-way ANOVA demonstrated that percent capture was significantly different between DAF operating at 1:1, 2:1, and 3:1 ratios ($P < 0.001$) (Table 3). However, results from a Fisher's multiple comparison test revealed that percent capture for 1:1 and 2:1 ratios were not statistically different ($P = 0.306$) (Table 3). Total solids concentration was statistically higher for a 1:1 ratio when compared to 2:1 and 3:1 operating ratios ($P < 0.001$) (Table 3). Dissolved air flotation operating at a 3:1 ratio did not maximize any operational parameters, which suggests excessive solids and hydraulic loading because of an inadequate A/S ratio.

Algae Removal with Suspended Air Flotation. The SAF operating ratios of 160:1, 120:1, and 80:1 were used to remove algae from wastewater. The small volumes of flotation water produced much lower A/S ratios when compared to DAF (Table 2). In turn, sample dilution because of flotation water introduction produced gradually decreasing solids and hydraulic loading rates, rather than a spike that was observed with DAF (Figure 2). Although results from a one-way ANOVA established that SAF operating at an 80:1 ratio had significantly higher solids and hydraulic loading rates when compared to 120:1 and 160:1 ($P < 0.001$), it also had the lowest percent capture (Table 4). The 63.3% percent capture of the 80:1 ratio was significantly less ($P < 0.001$) than the 76.6% and 70.1% achieved by 120:1 and 160:1 ratios, respectively (Table 4). Total solids concentration of harvested solids was not statistically different ($P = 0.111$) for 80:1, 120:1, or 160:1 operating ratios. Based on these results, SAF operating at a 120:1 ratio was determined to be the most efficient despite having a lower solids and hydraulic loading rate than the 80:1 ratio. This was because the higher percent capture of the 120:1 ratio will ultimately harvest solids more efficiently than the 80:1 ratio.

Comparing Dissolved and Suspended Air Flotation. Dissolved air flotation operating at a 2:1 ratio and SAF operating at a 120:1 ratio were selected as the basis for comparing thickening technologies. These ratios were selected because they provided most efficient operation. Suspended air flotation operating at a 120:1 ratio had an A/S ratio of 0.07 compared to the 0.34 required by DAF operating at a 2:1 ratio. The lower A/S ratio of SAF is most likely attributed to reduced surface tension between gas and liquid phases and electrostatic attractions between the solids and the cationic surfactant employed to produce the microbubbles (Al-

Table 5—Results from a two-sample t-test comparing of mean total solids concentration, solids loading rate, and hydraulic loading rate of dissolved air flotation (DAF) operating at a 2:1 ratio and suspended air flotation (SAF) operating at a 120:1 ratio [SE = standard error, n = sample size, mean = average value for each operational parameter, and P = level of statistical significance ($\acute{\alpha}$ = 0.05)].

Variable	DAF 2:1 ratio		SAF 120:1 ratio		n	P
	Mean	SE	Mean	SE		
Total solids concentration (%)	4.5	0.1	4.8	0.1	30	<0.001
Solids loading rate (g/min/m^2)	29.4	0.5	93.7	1.7	30	<0.001
Hydraulic loading rate (L/min/m^2)	267	4.1	620	12	30	<0.001
Percent capture	84.9	0.81	76.6	0.74	30	<0.001

Table 6—Results from a two-sample t-test comparing adjusted percent capture and initial solids loading for dissolved air flotation (DAF) and suspended air flotation (SAF) [SE = standard error, n = sample size, mean = average percent solids captured by DAF and SAF, and *P* = level of statistical significance (α = 0.05)].

Variable	DAF 2:1 ratio			SAF 120:1 ratio			
	Mean	SE	n	Mean	SE	n	*P*
Percent capture	84.9	0.81	30	83.4	0.69	12	0.166
Raw sample total suspended solids (mg/L)	110	2.8	3	114	3.1	3	0.318

Shamrani et al., 2002; Féris et al., 2001). These characteristics decreased rise time, enabling SAF to have greater solids loading and hydraulic loading rates. Additionally, the total solids concentration of material harvested with SAF was greater than that thickened with DAF operating at a 2:1 ratio (Table 5). Although this result is statistically significant, the differences may be attributed to variable concentrations of the feed sample. In addition, the slight differences (4.5% versus 4.8%) may be of little concern in actual practice.

Percent capture for DAF was 84.9% ± 0.81 and for SAF it was 76.6% ± 0.74. A two-sample t-test revealed that the two means were statistically different (*P* < 0.001). However, increased solids loading can decrease percent capture. During this study, the initial solids loading for SAF was significantly higher (319%) than that of DAF (*P* < 0.001) (Table 5). An adjusted percent capture analysis was performed with SAF operating at a 120:1 ratio to compensate for the increased solids loading when compared to DAF operation at a 2:1 ratio. This was accomplished by diluting the raw sample such that initial solids loading was not significantly different than that of DAF operating at a 2:1 ratio (*P* = 0.318) (Table 6). The adjusted percent capture of SAF operating at a 120:1 ratio was 83.4% ± 0.64 compared to 84.9% ± 0.81 of DAF operating at a 2:1 ratio. Results from a two-sample t-test indicated that the differences between the means were not statistically significant (*P* = 0.166) (Table 6).

Dissolved air flotation had significantly greater energy requirements when compared with SAF. The bench-scale DAF unit operating at a 2:1 ratio consumed 760 watt-hours for each 100 L of sample treated. In contrast, the SAF unit operating at a 120:1 ratio required 0.3 watt-hours for each 100 L of sample treated. As bench-scale systems were not designed to maximize energy efficiency, the scalability of this result is uncertain. However, it is likely that DAF will have greater energy requirements than SAF. This is because DAF saturators must be operated at pressures high enough to produce bubbles in the 10 to 100 micron range (Chung et al., 2000; French et al., 2000). Several studies have demonstrated that DAF flotation water must be pressurized at a minimum of 390 kPa (56 psi) to produce bubbles of suitable diameter (Al-Shamrani et al., 2002; Féris et al., 2001; Féris and Rubio, 1999). Insufficient DAF pressurization leads to larger bubbles that cause hydraulic disturbances and decreased net surface area, resulting in lower flotation efficiency (Al-Shamrani et al., 2002). In contrast, SAF produces bubbles of acceptable diameter with less pressure, more quickly. Furthermore, the lower A/S ratio used by SAF greatly reduces flotation water requirements. For example, DAF operating at a 2:1 ratio required 33 L of flotation water per 100 L of sample; whereas, SAF operating at a 120:1 ratio required 0.83 L of flotation water per 100 L of sample.

Conclusions

Although DAF had been identified as the most efficient method to harvest algae, this study demonstrated that under certain conditions, SAF could process greater volumes of sample more quickly and with less energy. Use of this technology may reduce financial barriers associated with algal harvesting currently faced by wastewater treatment facilities and manufactures of algal-based products.

This experiment measured the performance of SAF over a short period of time. Chemical dosing and surface charges of surfactants and polymers may need to be modified in response to system changes over time.

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