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Techno-economic Potential of Integrated Anaerobic Digestion and Aerobic Lipid Accumulation for Fuels and Materials Recovery from Wastewater Treatment Plants

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Abstract

The study focused on computational modelling and simulation experiments to perform techno-economic analysis of a conceptual process flow for the integration of anaerobic and aerobic bioprocesses inherent to wastewater treatment plants (WWTPs). The process models the production of organic acids (short chain fatty acids or SCFAs) from wastewater treatment sludges, i.e., primary sludge (PS) and waste activated sludge (WAS), through two-stage anaerobic digestion, which also produces biogas (CH_4 and CO_2) as by-product. The organic acids are then fed into an aerobic WAS microbial consortia cultivated through a sequencing batch reactor, which facilitates the gradual loading of the organic acids to minimize acid inhibition, and also facilitates settling and withdrawal of the lipid-enhanced microbial consortia. A lipidic-oil transesterification step and processing then takes the lipid-enhanced stream, anaerobic digestate, and excess PS for the recovery and conversion of lipids and oils into biodiesel with a solid by-product that is chemically stable and may be land-applied as fertilizer or soil amendment. Literature data on costs are also included to position the economic benefits of the proposed process.

Keywords: Techno-economic analysis; Waste management; Process modelling

Introduction

Resource recovery from wastewater treatment plants (WWTPs) has long been advocated and practiced in some parts of the world [1]. With more stringent regulations on the quality of the recovered resources [2], and the need for case-specific technologies [3], alternative recovery methods are desired in addition to conventional technologies [1]. The SCFAs-to-lipids transformation through activated sludge was envisioned as an alternative mass conversion pathway for organic wastes. This concept was predicated on the fact that some related conventional and emerging technologies can accomplish upstream and downstream processes to complete a system for the transformation of organic wastes to fuels and materials. A conceptual illustration of a proposal for such an integrated system is shown in Figure 1. The potential technical and economic performances of this system are evaluated in this work via order-of-magnitude estimations.

The model system considered here is linked to a wastewater treatment plant (WWTP), which simplifies the system model because the feedstock sludges are locally generated in WWTPs. Primary sludges (PS) are the settleable components of the grit-free raw wastewater passed through a primary thickener [1]. PS are dark gray and slimy agglomerations of mostly organic substances with traces of inorganic matter. Waste activated sludges (WAS) are the excess solids slurry generated in the aerobic biological treatment units, e.g. oxidation ditch, conventional activated sludge, and sequencing batch reactors. WAS are essentially activated sludges (AS) removed from WWTP. WAS mainly contain a consortia of aerobic microorganisms [1]. The WAS microbes grow by assimilating the soluble, colloidal or suspended organic substances in the wastewater. Therefore, WAS microbes are carbon and nitrogen sinks in WWTPs.

In the proposed integrated system (Figure 1), the SCFAs fed as carbon substrates to the WAS lipid accumulation stage are produced upstream via two-phase anaerobic digestion of sludges, and the lipid-enhanced WAS are sent to transesterification for the production of biodiesel. Biogas is a by-product of anaerobic digestion, and Class-A biosolids is a by-product of transesterification.

Two-phase anaerobic digestion

Two-phase anaerobic digestion is a modification of the conventional anaerobic digester. It maximizes the production of SCFAs and biogas in separate (but connected) sections (or digesters) by maintaining different culture conditions via manipulation of operational parameters such as temperature, and retention times of liquid and solid phases. The biosolids produced from this process usually meets Class-A pathogen reduction requirements [4], so these can be applied to lawns, home gardens, or other types of land, or bagged for sale. These digested biosolids can still contain around 3% (w/w) lipids [5]. The biogas produced can be cleaned and fed into a combined heat-and-power (CHP) turbine generator for electricity and heat supply. Past studies showed that CHP unit significantly reduces the operational cost not for the digesters but also for other plant sections [6].

Activated sludge lipid accumulation

The WAS microorganisms will use short chain fatty acids (SCFAs) from the two-phase anaerobic digestion by cultivation under aeration,

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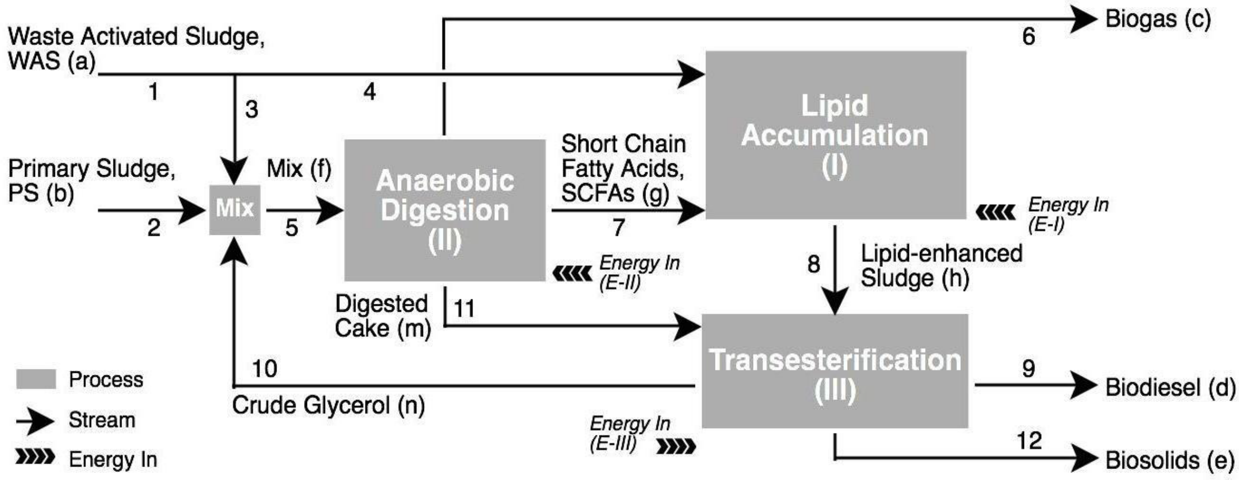

Figure 1: Proposed integrated system employing SCFAs-to-lipids conversion. Annotations of numbers and letters denote stream and components respectively.

and fed-batch loading of the SCFAs [7]. The study proposes the use of sequencing batch reactor (SBR) system, which was originally developed as an alternative activated sludge process [8]. This system consists of two or more reaction vessels operated in synchronized fill-and-draw cycles to accommodate continuous flow of incoming streams of AS and SCFAs. Each tank is filled with the liquid stream containing SCFAs and with the stream of AS during a discrete period of time, operated in batch mode with aeration, allowed to stand without aeration to settle the AS solids, pumped out of the spent liquid (exhausted of SCFAs) while retaining most of the AS solids, and then filled with the liquid stream containing SCFAs for another cycle. The cycle is repeated until some set parameters are met, e.g., number of cycles, or AS solids concentration.

Trans-esterification

The lipids in the activated sludge and in the digestion cake can be trans-esterified into biodiesel. This process involves acid-catalyzed reaction of enhanced AS lipids, which are mostly triglycerides (TAGs), with methanol at slightly elevated temperature (75°C) for 2 hours [9-11]. Separation of biodiesel from glycerol is via distillation as simulated previously by You, Shie [12]. Part of this technology is a set of settlers and distillation columns for the separation of biodiesel from the spent biomass and glycerol. The separation units can also recycle methanol to minimize production costs.

Materials and Method

Techno-economic evaluation

The main components of the techno-economic evaluation are feedstock flow rates, process performance parameters, simulation algorithm, and economic analysis. The system is assumed to be at steady state operation. The process simulation is an order-of-magnitude estimation (ratio estimate) based on mass yields of stream key components in the three technologies. This simplicity of simulation is the result of the current lack of rigorous models for chemical, physical, biochemical, and thermodynamic properties of AS and PS. A major limitation of this simulation approach, therefore, is the lack of means to check for atomic mass balancing in the whole system. Nonetheless, appropriate literature data on mass conversions were used to compensate for the potential shortcomings in atomic mass balancing. The calculations were executed in MATLAB® (Matrix Laboratory, Math Works Inc.).

Input feed stocks

Data sets on the mass flow rates for each type of sludge were extracted from an operation database of a nearby WWTP (Ambassador Caffery WWTP, Lafayette LA 70503; Map: 30°09'49"N, 92°03'28"W). The plant data were for the years 2013, 2014 and 2015. The distributions of the mass flow rates of WAS and PS are shown in Figure 2.

Several probabilistic distribution models were tested to fit the data distribution (Table 1), and Weibull distribution showed the best fit to both the data sets based on minimum error-square calculated using Input Analyzer software (Version 12.00.00, by Rockwell Automation).

Process performances

The transformation of the key stream components was calculated based on mass conversion parameters summarized in Table 2.

Two-phase anaerobic digestion maximizes the production of SCFAs and biogas in separate (but connected) sections (or digesters) by maintaining different culture conditions via manipulation of operational parameters such as temperature, and retention times of liquid and solid phases [13]. The biosolids produced from this process usually meet Class A pathogen reduction requirements [4], so these can be applied to lawns, home gardens, or other types of land, or bagged for sale [2]. These digested biosolids can still contain around 3% (w/w) lipids [5]. The biogas produced can be cleaned and fed into a combined heat-and-power (CHP) turbine generator for electricity and heat supply [14]. The lipids in the activated sludge and in the digestion cake can be trans-esterified into biodiesel [11,15]. This process involves the acid-catalyzed reaction of enhanced AS lipids, which are mostly triglycerides (TAGs) [15], with methanol at a slightly elevated temperature (75°C) for 2 hours. Separation of biodiesel from glycerol is via distillation as simulated previously by You, Shie [12].

Simulation algorithm

The set of relations used to perform the calculations on mass conversions are shown in Table 3. The notations are based on the process flow diagram in Figure 1. The perturbations in the values of WAS and PS were accounted for by simulating the best-fit (Table 1)

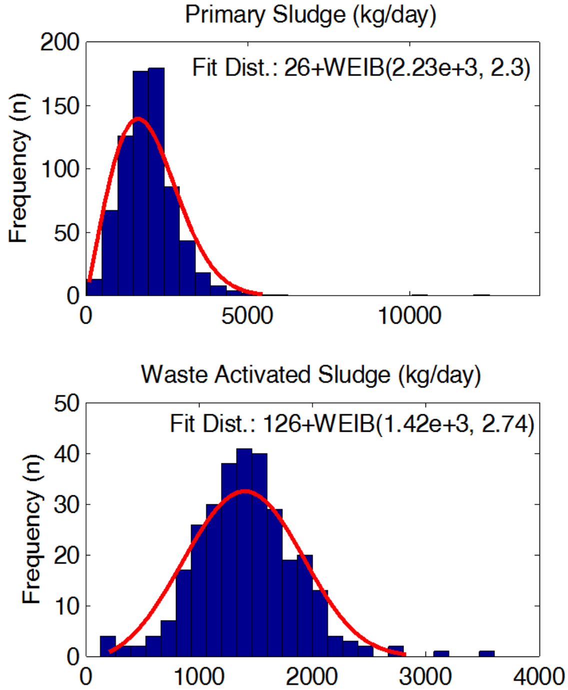

Figure 2: Distribution of WAS and PS mass flows (kg/day) at the Ambassador Caffery WWTP for years 2013-2015.

Probabilistic Model		Error-square
PS (kg/day), (Ave.: 1,960; Std. Dev.:956)		
Weibull	26+WEIB(2.23e+3, 2.3)	0.0078*
Erlang	26+ERLA(483, 4)	0.00942
Gamma	26+GAMM(491, 3.94)	0.00967
Lognormal	26+LOGN(2.23e+3, 1.91e+3)	0.0367
WAS (kg/day), (Ave.: 1,420; Std. Dev.: 456)		
Weibull	126+WEIB(1.42e+3, 2.74)	0.00773*
Gamma	126+GAMM (316, 4.09)	0.0212
Erlang	126+ERLA (323, 4)	0.0217
Lognormal	126+LOGN (1.78e+3, 2.13e+3)	0.0676
*Best fit model.		

Table 1: Error-squares of fitted probabilistic models for PS and WAS distribution.

Parameter	Value	Units	Source
Two-phase Anaerobic Digestion			
Biogas yield from sewage sludge[a], $Y_{c,a,II}$, $Y_{c,b,II}$, $Y_{c,n,II}$	0.76[b]	m^3/kg VS-digested	[13]
SCFAs (as HAc[c]) yield from sewage sludge[a], $Y_{g,ab,II}$	0.48	kg/kg VS-digested	[16]
Sludge VS[d] digested, $X_{VS,p,II}$	0.45	kg/kg VS-added	[17]
VS in AS (WAS), $f_{VS,a}$	0.69	kg/kg	[17]
VS in PS, $f_{VS,b}$	0.84	kg/kg	[17]
Lipid accumulation			
AS biomass yield from SCFAs, $Y_{m,I}$	0.448	kg/kg	[7,18,19]
Lipid content of AS, $f_{lipid,h}$	0.12	kg/kg	[7,18,19]
Lipid content of digested cake, $f_{lipid,m}$	0.03	kg/kg	[5]
Transesterification			
Biodiesel yield from AS, $Y_{d,h,III}$	0.4	kg/kg lipid	[7,18,19]
Biodiesel yield from digested cake, $Y_{d,m,III}$	0.4	kg/kg lipid	[11]
Crude glycerol-to-biodiesel ratio, $f_{n/d}$	0.1	kg/kg	[20]
[a]Reference(s) used two-stage anaerobic digestion, [b]Density of biogas is approximately 1-kg/m^3 [13], [c]HAc-acetic acid, [d]VS-volatile solids.			

Table 2: Performance parameters for the three technologies.

distribution models for 365 sampling (N=365 days) to model an annual operation. The same sets of simulated samples of WAS and PS were used for the various simulation runs in order to allow for comparison of the simulation results (Table 3). The split fraction of WAS sent to anaerobic digestion was varied from 0 to 0.5 to evaluate the sensitivity of the system with varying usage of the feedstock. An iteration loop was used to handle the recycle stream ($M_{n,10}$). The details of the algorithm implemented in MATLAB® are shown in Table 3.

Economic analysis

The economics of the system was analyzed by estimating costs and revenues. Like the mass conversion calculations, costs and revenues estimates were determined through order-of-magnitude approach. Costs include total capital investment and total annual operation costs. Revenues include sales of products electricity, biodiesel and Class-A biosolids.

Capital costs: On the capital costs, capacity-associated costs were estimated using economy-of-scale ratios on previous detailed capital cost analyses. Inflation-associated aspects of costs were accounted using cost indexing. The combined effects of these two cost adjustments are expressed in Equation 25, where C_t is the cost estimate for a target capacity ($Capacity_t$) at an analysis time, C_b is the cost estimate of a capacity basis ($Capacity_b$) of a similar process plant sometime in the past, I_t is the cost index at the target analysis time, and Ib is the cost index at the time of cost estimation of the base capacity. The exponent n may vary from 0.38 to 0.90, and the typical value is 0.60, which is regarded as the "sixth-tenths rule" [21]. The economic indicators catalogue of Chemical Engineering (CE) magazine was used for process plant cost indexing. Table 4 summarizes the capacities and cost indices used for the estimation of capital costs.

These total capital costs already accounted the calculation of contingencies and fees, total basic module costs, auxiliary facility costs, fixed capital costs and working capitals.

$$C_t = C_b \left(\frac{Capacity_t}{Capacity_b} \right)^n \left(\frac{I_t}{I_b} \right) \tag{25}$$

Operating and maintenance costs: Operating and maintenance costs consist of costs associated with utilities, feedstocks (raw materials), labor, maintenance, operating overhead, taxes and insurance, and depreciation. Some of the economic factors used to calculate the operating and maintenance costs are summarized in Tables 5-7.

Revenues: Revenues come from the sale of biodiesel, biosolids and electricity. Also accounted for is the revenue from treating the waste sludges from WWTP. The estimated prices of these are summarized in Table 8.

Results and Discussion

Some of the results of the simulations are shown in Figures 3 and 4. Evident in these results are the fluctuations of the mass flows. The average values and associated standard deviations of the various mass flows are summarized in Table 9. A trade-off exists between the biogas, and biodiesel and biosolids production. As more of the WAS is fed into the anaerobic digestion unit, together with PS, more biogas is produced. This results in fewer feedstocks for lipid accumulation and, consequently, less biodiesel and biosolids coming out of the trans-esterification section.

This splitting of WAS as a feedstock to anaerobic digestion, and as a feedstock to lipid accumulation significantly affects the economics of the system (Tables 10-14). As more WAS is fed into anaerobic digestion, the capital cost for the anaerobic digestion section increases, while the capital cost for the lipid accumulation decreases at much larger increments (Table 10). The capital cost for the transesterification section is constant due to the threshold (minimum) design sizing (Table 10). These results in decreased overall capital costs for the system infrastructure as more WAS is directed to anaerobic digestion. The major components of the annual production cost are also correlated to the level of WAS split fraction (Table 11).

Direct operating cost, indirect operating cost, and depreciation decreases with increasing amount of WAS digested. The general expenses, on the other hand, increases due to increasing revenue (Table 12). Electricity is the dominant portion of the revenue. Even when the amounts of biodiesel and biosolids sold decrease with more WAS digested, the revenue on the surplus electricity from anaerobic digestion increases with the highest margin. The combined heat and power (CHP) unit in the anaerobic digestion section provides more than enough heat and power for the system demand (Table 13). There is no profit for the system even at varying fractions of the WAS sent to the digester (Table 14).

Increasing the fraction of WAS directed to the digester reduces the deficit, but there is no chance for payback. Increasing the selling prices of the three products allows for break-even of the production costs and revenues. The breakeven price of each product was estimated by making the other cost items constant (Table 14). For example, when biodiesel breakeven price was determined, the selling price of biosolids, electricity, and sludge treatment were maintained at the literature values (Table 8). Interesting patterns are observed on these breakeven prices as more WAS are directed to the digester (increasing x). The breakeven price of electricity starts at its highest when no WAS is digested (x=0),

Eq'n No.	Relation
1	N=365 (to simulate 365 days of operation per year)
2	$x=M_{a,3}/M_{a,1}$ (varied from 0 to 0.5)
3	$M_{a,1}=126+\text{WEIBULL}(1.42e+3, 2.74, N)$
4	$M_{b,2}=26+\text{WEIBULL}(2.23e+3, 2.3, N)$
5	$M_{a,3}=x \times M_{a,1}$
6	$M_{a,4}=M_{a,1}-M_{a,3}$
7	$M_{f,5=}M_{a,3}+M_{b,2}+M_{n10}$
8	$M_{c,a}=Y_{c,a,II} \times F_{VS,a} \times X_{VS,p,II} \times M_{a,3}$
9	$M_{c,b}=Y_{c,b,II} \times F_{VS,a} \times X_{VS,p,II} \times M_{b,2}$
10	$M_{c,n=}Y_{c,n,II} \times M_{n,10,old}$
11	$M_{c,6}=M_{c,a}+M_{c\ b}+M_{c,n}$
12	$M_{g,a}=Y_{h,a,II} \times F_{VS,a} \times X_{VS,p,II} \times M_{a,3}$
13	$M_{g,b}=Y_{h,b,II} \times F_{VS,b} \times X_{VS,p,II} \times M_{b,2}$
14	$M_{g,n}=Y_{h,n,II} \times M_{n,10}$
15	$M_{g,7}=M_{ga}+M_{gb}+M_{g,n}$
16	$M_{m,1}=F_{VS,a} \times (1-X_{VS,p,II}) \times (M_{b,2}+M_{a,3})$
17	$M_{h,8}=Y_{m,I} \times M_{g,7}+M_{a,4}$
18	$M_{lipid}=F_{lipid,h} \times M_{h,8}+F_{lipid,m} \times M_{m,11}$
19	$M_{d,9}=Y_{d\ h\ III} \times M_{lipid}$
20	$M_{e,12}=M_{m,11}+M_{h,8}-M_{d,9}-M_{n,10,old}$
21	$M_{n,10,new}=F_{n/d} \times M_{d,9}$
22	$M_{in}=M_{a,1}+M_{b,2}$
23	$M_{out}=M_{c,6}+M_{d,9}+M_{e,12}$
24	$M_{n,10,iter}=M_{n,10,new}-M_{n,10,new}$ (Iterated until<0.01)
$M_{i,j,k}$ is mass flow rate in (kg/day), x is the split mass fraction of WAS from stream 1 to stream 3	

Table 3: Mass conversions algorithm.

Process	Base Capacity and Capital Cost	Base Cost Index (I_i)[a]
Anaerobic Digestion	Capacity: 15,000 tons solids/year [22] Total Capital Cost: $2,000,000 [22] Base year: 2010 System: Two-stage anaerobic digesters; combined heat and power (CHP) turbine-generator; biogas (30-40% CH_4 and 60-70% CO_2) cleanup units: chillers, moisture separators, hydrogen sulfide removal vessels, siloxane removal vessels, heat exchangers, blowers, piping; cake belt press[13,14,22] Organic Loading Rate:600 kg-VS/m³/day [4]	550.8 (Year 2010) [23]
Lipid Accumulation	Capacity: 379 m³ working volume/day Total Capital Cost: $195,000 Base year: 1985 System: Sequencing batch reactor (SBR) vessels; inlet control system; aerators; pumping system; engineering, and construction Solids Retention Time: 5 days [b] [8]	325.3 (Year 1985) [24]
Trans-esterification	Capacity: 3.07 × 10⁵ gallons biodiesel/year [10], Size: Total Capital Cost: $490,00 [10], Base year: 2008, System: Trans-esterification reactor; neutralization reactor; washing column; distillation columns for biodiesel recovery; heat exchangers; pumps [10,12]	575.4 (Year 2008) [25]

[a]Annual average cost indices were from the catalogue of Chemical Engineering (CE) magazine. The first cost index was at 100 in year 1957. The average cost index in CE for 2014 is 576.1 [26]. [b]This is the solids (activated sludge) retention time used in the fed-batch experiments [7]. [c]Revellame, Hernandez [9] found that moisture content less than 50% allows economical trans esterification of wet activated sludge.

Table 4: Base capacities and cost indices for capital cost estimation.

Utilities	Usage	Cost
	Anaerobic Digestion	
Electricity	9.17 kWh/MT solids [27]	Generated in plant
Heat	42.2 kWh/MT solids [27]	Generated in plant
	Lipid Accumulation	
Electricity	102 kWh/day per 379 m³/day [8][a]	Generated in plant
	Transesterification	
Electricity	1,330 kWh/MT lipids [28]	Generated in plant
Heat	3,118 kWh/MT lipids[b]	Generated in plant

MT: Metric Ton (1000 kg); 1 kWh=3.6 megajoules (MJ). [a]Includes electricity used for aeration, decanting, and pumping of streams [8]. [b]Derived from steam requirement of 497,422 MT/100,000 MT lipids reported by Park, Fei [28]; Heat in steam was calculated using latent heat of vaporization of saturated steam (1 bar), 970 BTU/lb (or 627 kWh/MT) [29].

Table 5: Utilities in the three technologies.

Energy content of biogas[a]	27.8 MJ/m³ [17]
CHP overall energy efficiency	83% [6]
Electricity from overall energy	50-70% [6]
Heat from overall energy	30-50% [6]

[a]Biogas density is 1 kg/m³ [13]. 1 kWh=3.6 megajoules (MJ).

Table 6: Accounting of heat and power generation from biogas using CHP turbine-generator system at the anaerobic digestion section.

Feedstock	Usage	Unit Cost
	Anaerobic Digestion	
Sludge (WAS and PS)	Simulated	Generated in plant
	Lipid Accumulation	
WAS	Simulated	Generated in plant
SCFAs	Simulated	Generated in plant
Wash water	Variable	Generated in plant
	Transesterification	
Lipid-enhanced AS	Simulated	Generated in plant
Digested cake	Simulated	Generated in plant
Methanol[a]	8 kg/kg sludge [10]	$503/MT [30]
Sulfuric acid	0.05 kg/kg methanol [10]	$750/MT [31]
Process water	157 kg/kg lipid [28]	$0.05/MT [28]
Wash water	Variable	Generated in plant

[a]Recovery of 94% of methanol is possible according to simulations by You, Shie [12]. Costs are based on year 2014 data. 1 kWh=3.6 megajoules (MJ).

Table 7: Feedstocks in the three technologies.

and it monotonously decreases as more WAS are digested. The same trend is followed by the breakeven price of biosolids. These decreasing trends are due to the increasing production of biogas and biosolids as more sludges (PS and WAS) are digested. The breakeven price for biodiesel, on the other hand, follows an opposite trend. As more WAS are digested, the higher the breakeven price for biodiesel. This is due to the decreasing production of biodiesel as more WAS are directed from lipid accumulation to anaerobic digestion. Higher price compensates for the decreasing production rate of the biodiesel to achieve breakeven.

Biodiesel[a]	$4.50/gal [29-32]
Biosolids	$0.06/kg [4]
Electricity[b]	$0.11/kWh [33]
Waste sludge treatment	$0.045/kg [21]
[a]Biodiesel density is 900 kg/m^3 (3.41 kg/gal) [34]. [b]Pricing used was the average of the West South Central US region that includes Louisiana.	

Table 8: Market prices of outputs. Prices are based on year 2014 data.

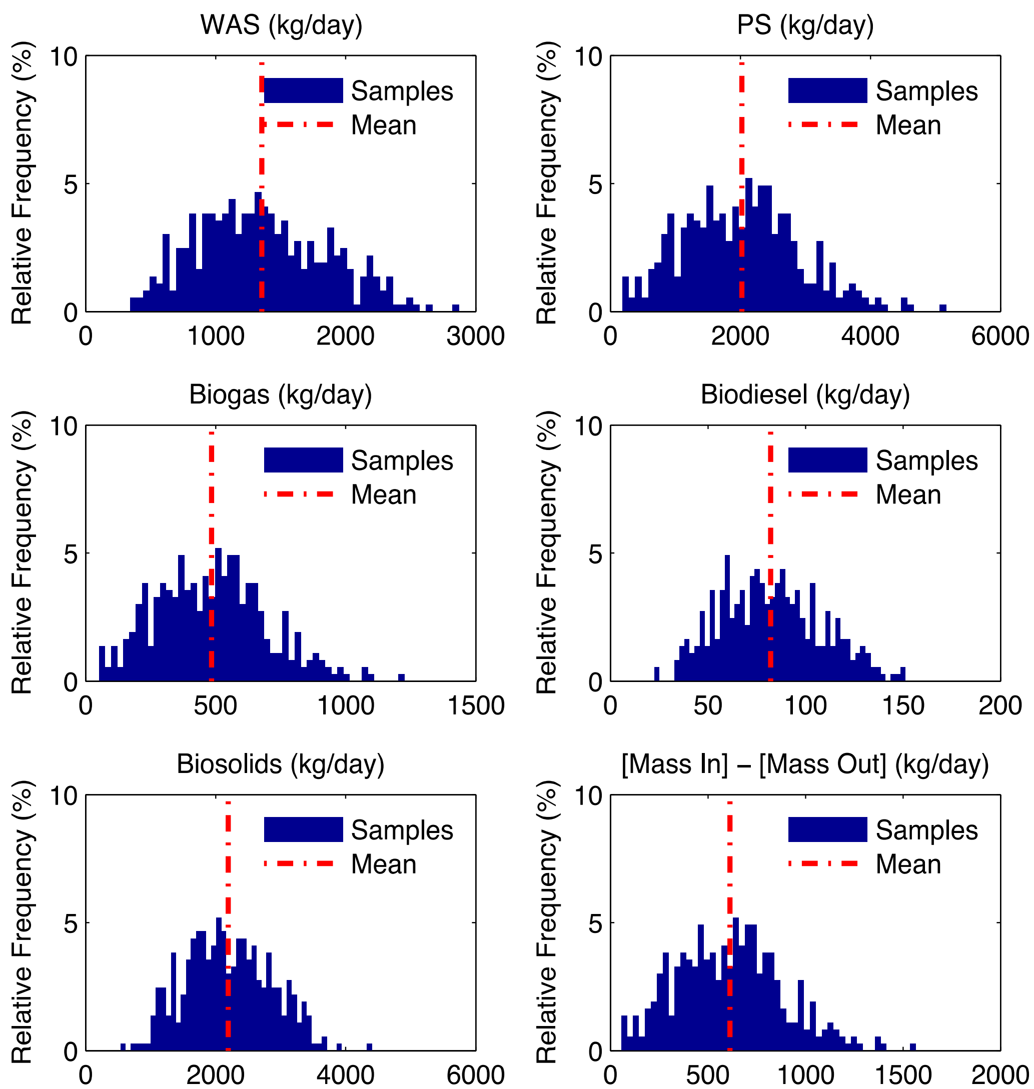

Figure 3: Sample mass conversion simulation results at x=0.

Conclusions

Techno-economic analysis of the integration of lipid accumulation with anaerobic digestion and trans-esterification revealed the potential capabilities and limitations of the integrated system. This was implemented via material conversion simulations and cost analyses. All primary sludges (PS) were directed to a 2-stage anaerobic digestion section while some waste activated sludges (WAS) were digested and the rest directed to an aerobic lipid accumulation section, which was proposed to operate as sequencing batch reactor (SBR) system. Anaerobic digestion positively contributes to the system via biogas production. The electricity and heat produced from anaerobic digestion biogas can support the demand of the whole system. Surplus electricity can be sold in addition to the biodiesel and Class-A biosolids products. The by-product short chain fatty acids (SCFAs) from the anaerobic digestion section were directed to the lipid accumulation section to function as carbon sources for WAS. The lipid-enhanced activated sludges were sent to a transesterification section to produce biodiesel. The low production rate of biodiesel limited the design sizing of the transesterification reactors and columns such that the economy-of-scale assumption cannot hold. This required the assumption of a threshold (minimum) design sizing, which resulted to a high capital cost on the transesterification section. Negative profit (deficit) occurred even in all process design evaluations. Significant increase in the prices of biodiesel, biosolids and electricity were needed to achieve breakeven. These results imply that further improvements on the lipid

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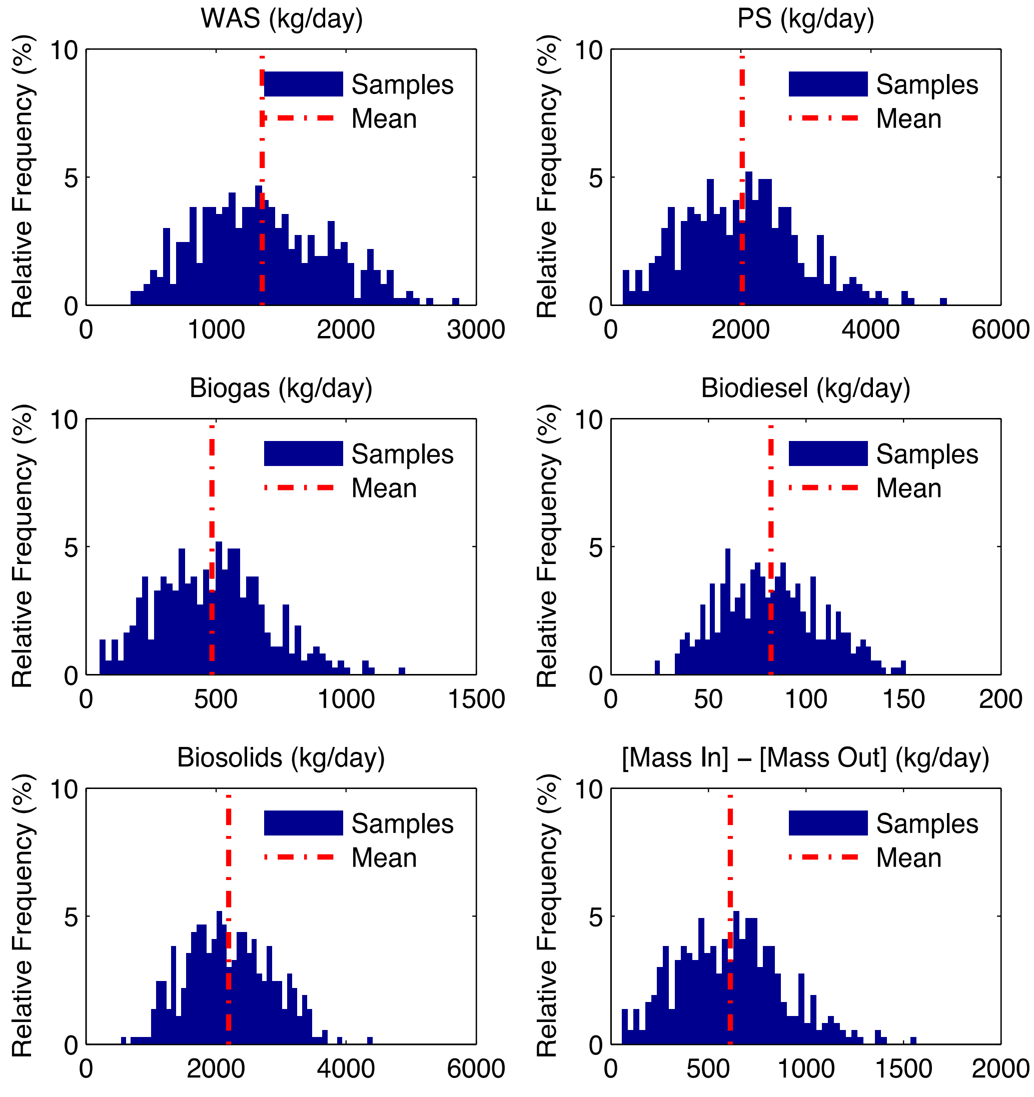

Figure 4: Sample mass conversion simulation results at x=0.5.

Scenario	1 x=0	2 x=0.1	3 x=0.2	4 x=0.3	5 x=0.4	6 x=0.5
WAS, $M_{a,1}$	1,355 (497)	1,355 (497)	1,355 (497)	1,355 (497)	1,355 (497)	1,355 (497)
PS, $M_{b,2}$	2,020 (905)	2,020 (905)	2,020 (905)	2,020 (905)	2,020 (905)	2,020 (905)
Biogas, $M_{c,6}$	484 (213)	516 (215)	548 (217)	580 (220)	612 (224)	644 (228)
Biodiesel, $M_{d,9}$	82 (32)	77 (24)	71 (22)	65 (20)	60 (18)	55 (17)
Biosolids, $M_{e,12}$	2,195 (661)	2,128 (641)	2,056 (622)	1,987 (603)	1,917 (584)	1,848 (566)
M_{in}-M_{out}	613 (274)	656 (277)	699 (280)	742 (284)	785 (289)	828 (294)
M_{lipid}	206 (65)	192 (60)	178 (55)	165 (51)	151 (46)	137 (41)
$M_{a,3}$	0 (0)	135 (50)	271 (99)	407 (149)	542 (199)	677 (248)
$M_{a,4}$	1,355 (497)	1,220 (447)	1,084 (397)	948 (348)	813 (298)	677 (248)
$M_{f,5}$	2,030 (905)	2,165 (912)	2,301 (922)	2,436 (934)	2,572 (949)	2,707 (966)
$M_{g,7}$	371 (164)	391 (165)	412 (167)	432 (168)	452 (170)	472 (172)
$M_{h,8}$	1,521 (511)	1,395 (465)	1,268 (420)	1,142 (374)	1,015 (328)	889 (283)
$M_{n,10}$	8.2 (2.6)	7.7 (2.4)	7.1 (2.2)	6.6 (2)	6.0 (1.8)	5.5 (1.6)
$M_{m,11}$	766 (343)	818 (346)	869 (350)	921 (355)	927 (360)	1,024 (367)

Note: Numbers inside parentheses are standard deviations. x is the split mass fraction of WAS from stream 1 to stream 3.

Table 9: Average mass flows (kg/day) of stream components from simulations.

Process	x	Size	Capital Cost ($)
Anaerobic digestion	0	566[a]	344,154
	0.1	597[a]	357,709
	0.2	628[a]	371,026
	0.3	660[a]	383,938
	0.4	691[a]	396,660
	0.5	722[a] m^3	409,023
Lipid accumulation[b]	0	226[c]	253,127
	0.1	203[c]	237,679
	0.2	181[c]	221,408
	0.3	158[c]	204,296
	0.4	136[c]	186,307
	0.5	113[c] m^3	166,928
Trans-esterification	0	The economy of scale, Equation 25, cannot be used in this section because the projected capacities are very small and will result to infeasible design. The estimates of Mondala, Liang [10] were used as the threshold (minimum) size: Transesterification reactor: D × L: 1 m × 2.5 m Neutralization reactor: D × L: 0.2 m × 0.3 m Washing column: D × H: 0.4 m × 5 m FAMEs distillation column: D × H: 0.6 m × 6.5 m	490,000
	0.1		490,000
	0.2		490,000
	0.3		490,000
	0.4		490,000
	0.5		490,000
Total capital cost (TCC)	0		1,087,280
	0.1		1,085,388
	0.2		1,082,434
	0.3		1,078,234
	0.4		1,072,966
	0.5		1,065,950

Fixed capital cost (FCC)=TCC/1.15 [12]; Working capital (WCC)=15% FCC [12]; TCC=FCC+WCC. x is the split mass fraction of WAS from stream 1 to stream 3, [a]Maximum working volume of each digester in a 2-stage configuration, [b]Volumetric capacity was calculated using AS solids concentration of 30-g/L and residence time of 5 days, [c]Total working volume of 2-reactor assembly.

Table 10: Capital cost estimates for the proposed system.

Item	Annual Cost ($)					
	x=0	x=0.1	x=0.2	x=0.3	x=0.4	x=0.5
A. Direct operating costs	1,63,800	1,62,771	1,61,654	1,60,488	1,58,700	1,57,896
1. Feedstocks	27,661	26,745	25,806	24,892	23,420	23,037
Methanol	25,193 (50)[a]	24,378 (48)[a]	23,541 (47)[a]	22,725 (45)[a]	21,392 (43)[a]	21,073 (42)[a]
Sulfuric acid	1,878 (2.5)[a]	1,817 (2.4)[a]	1,755 (2.3)[a]	1,694 (2.3)[a]	1,595 (2)[a]	1,571 (2)[a]
Process water	590 (11.8)[b]	550 (11)[b]	510 (10.2)[b]	473 (9.5)[b]	433 (8.7)[b]	393 (7.9)[b]
2. Operating and maintenance	1,36,139	1,36,025	1,35,848	1,35,596	1,35,280	1,34,859
Labor (L)[c]	61,654	61,654	61,654	61,654	61,654	61,654
Lab charges[d]	9,248	9,248	9,248	9,248	9,248	9,248
Maintenance and repairs(MR)[e]	56,728	56,629	56,475	56,256	55,981	55,615
Operating supplies[f]	8,509	8,494	8,471	8,438	8,397	8,342
B. Indirect operatingcosts	27,314	27,274	27,212	27,123	27,012	26,864
Overhead (OH)[g]	8,405	8,398	8,387	8,372	8,352	8,326
Taxes[h]	14,182	14,157	14,119	14,064	13,995	13,904
Insurance[i]	4,727	4,719	4,706	4,688	4,665	4,635
C. Depreciation[j]	75,637	75,505	75,300	75,008	74,641	74,153
D. General expenses	14,629	14,792	14,919	15,046	15,201	15,356
Administrative expenses[k]	2,101	2,100	2,097	2,093	2,088	2,082
Distribution and selling[l]	2,160	2,188	2,211	2,233	2,261	2,289
Research and developmen[m]	10,368	10,504	10,611	10,720	10,852	10,986
Total production cost (PC)	2,81,381	2,80,342	2,79,084	2,77,665	2,75,555	2,74,269

Numbers in parentheses are annual usage rates. x is the split mass fraction of WAS from stream 1 to stream 3. [a]Annual usage in MT/year, [b]Annual usage in × 1000 MT/year, [c]3 operators, 8-h shift per day, $24/h, [d]15% of L, FCC=Capital cost/1.15, [e]6% of FCC, [f]15% of MR, [g]7.1% of MR+L, [h]1.5% of FCC, [i]0.5% of FCC, [j]8% of FCC, [k]25% of OH, [l]1% of SL, [m]4.8% of SL.

Table 11: Production cost estimates for the proposed system.

Item	Annual Sale ($)		
	x=0	x=0.1	x=0.2
Biodiesel[a]	39,497(12,419)	37,089(11,662)	34,199(10,753)
Biosolids[b]	48,071(801)	46,603(777)	45,026(750)
Electricity[c]	72,999(659,187)	79,704(724,582)	86,411(782,533)
Sludge treatment[d]	55,434(1,232)	55,434(1,232)	55,434(1,232)
Total sale (SL)	2,16,001	2,18,830	2,21,070
	x=0.3	x=0.4	x=0.5
Biodiesel[a]	31,309(9,844)	28,900(9,087)	26,492(8,330)
Biosolids[b]	43,515(725)	41,982(700)	40,471(675)
Electricity[c]	93,065(846,042)	99,770(906,997)	106,477(967,972)
Sludge treatment[d]	55,434(1,232)	55,434(1,232)	55,434(1,232)
Total sale (SL)	2,23,323	2,26,087	2,28,874

Numbers in parentheses are annual production rates. x is the split mass fraction of WAS from stream 1 to stream 3. [a]Production rate is in gal/year. [b]Production rate is in MT/year. [c]Production rate is in kWh/year. [d]Production rate is in 1 year=365 days; MT/year. MT: Metric Ton (=1000 kg).

Table 12: Revenue estimates for the proposed system.

	x=0	x=0.1	x=0.2
Production			
Biogas flow (kg/day)	484	516	548
Energy from biogas (MJ/day)	3,738	3,985	4,232
CHP output energy (MJ/day)	3,102	3,307	3,512
Heat production (kWh/day)[a]	931	992	1,054
Electricity production (kWh/day)[b]	2,172	2,315	2,459
Consumption			
Heat, AD (kWh/day)	86	91	97
Heat, TRANS (kWh/day)	642	599	555
Total Heat Use (kWh/day)	728	690	652
Electricity, AD (kWh/day)	19	20	21
Electricity, LA (kWh/day)	73	55	49
Electricity, TRANS (kWh/day)	274	255	237
Total electricity Use (kWh/day)	366	330	306
Surplus			
Available heat (kWh/day)	203	302	402
Available electricity (kWh/day)	1,818	1,985	2,152
	x=0.3	x=0.4	x=0.5
Production			
Biogas flow (kg/day)	580	612	644
Energy from biogas (kWh/day)	4,479	4,726	4,973
CHP output energy (kWh/day)	3,717	3,923	4,128
Heat production (kWh/day)[a]	1,115	1,177	1,238
Electricity production (kWh/day)[b]	2,602	2,746	2,889
Consumption			
Heat, AD (kWh/day)	103	109	114
Heat, TRANS (kWh/day)	514	471	427
Total heat usage (kWh/day)	617	579	541
Electricity, AD (kWh/day)	22	24	25
Electricity, LA (kWh/day)	43	36	30
Electricity, TRANS (kWh/day)	219	201	182
Total electricity usage (kWh/day)	284	261	237
Surplus			
Surplus heat (kWh/day)	498	597	697
Surplus electricity (kWh/day)	2,318	2,485	2,652

x is the split mass fraction of WAS from stream 1 to stream 3. AD-anaerobic digestion; LA-lipid accumulation; TRANS-transesterification. 1 year=365 days; 1 kWh=3.6 megajoules (MJ). [a]30% of CHP output energy; [b]70% of CHP output energy.

Table 13: Energy accounting in the anaerobic digestion CHP system.

Measure	x=0	x=0.1	x=0.2
Annual production cost, PC ($/year)	2,81,381	2,80,342	2,79,084
Annual revenue, SL ($/year)	2,16,001	2,18,830	2,21,070
Annual profit, P ($/year)	(-65,380)	(-61,512)	(-58,014)
Total capital cost, TCC ($)	10,87,280	10,85,387	10,82,014
Simple payback period (years)[a]	n.a.	n.a.	n.a.
Breakeven biodiesel price ($/gal)[b]	11.949	11.963	12.134
Breakeven biosolids price ($/kg)[b]	0.142	0.139	0.137
Breakeven electricity price ($/kWh)[b]	0.209	0.195	0.184
Measure	**x=0.3**	**x=0.4**	**x=0.5**
Annual production cost, PC ($/year)	2,77,665	2,75,555	2,74,269
Annual revenue, SL ($/year)	2,23,323	2,26,087	2,28,874
Annual profit, P ($/year)	(-54,342)	(-49,468)	(-45,395)
Total capital cost, TCC ($)	10,78,234	10,72,966	10,65,950
Simple payback period (years)[a]	n.a.	n.a.	n.a.
Breakeven biodiesel price ($/gal)[b]	12.311	12.203	12.211
Breakeven biosolids price ($/kg)[b]	0.135	0.131	0.127
Breakeven electricity price ($/kWh)[b]	0.174	0.165	0.157

x is the split mass fraction of WAS from stream 1 to stream 3.[a]Calculated only when the profit is positive; Equal to TCC/P in years, [b]Calculated only when the profit is negative assuming ceteris paribus (Latin), meaning "holding other things constant".

Table 14: Profitability measures for the proposed system.

enhancement of WAS must be explored to achieve a feasible integration of this technology to anaerobic digestion and transesterification.

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