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 (CH4 and CO2) 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 lipid–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,
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. 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.

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

| 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 2:** Performance parameters for the three technologies.

| Parameter | Value | Units | Source |
|-----------|-------|-------|--------|
| Two-phase Anaerobic Digestion |
| Biogas yield from sewage sludge, \( Y_{c,a,II} \) | 0.76\(^{\circ}\) | m\(^3\)/kg VS-digested | [13] |
| SCFAs (as HAc\(^{\circ}\)) yield from sewage sludge, \( Y_{c,b,II} \) | 0.48 | kg/kg VS-digested | [16] |
| Sludge VS\(^{\circ}\) 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, \( Y_{e,II} \) | 0.448 | kg/kg | [7,18,19] |
| Lipid content of AS, \( f_{lipid,a} \) | 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, \( Y_{d,a,III} \) | 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] |

\(^{\circ}\)Reference(s) used two-stage anaerobic digestion, \(^{\circ}\)Density of biogas is approximately 1-kg/m\(^3\) [13], \(^{\circ}\)HAc-acetic acid, \(^{\circ}\)VS-volatile solids.
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 \(C_i\) is the cost estimate for a target capacity \((Capacity_i)\) at an analysis time, \(C_0\) is the cost estimate of a capacity basis \((Capacity_0)\) of a similar process plant sometime in the past, \(I_i\) is the cost index at the target analysis time, and \(I_0\) 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 “six-tenths rule” [21]. The economic indicators 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.

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 transesterification 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 break-even price of each product was estimated by making the other cost items constant (Table 14). For example, when biodiesel break-even 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 break-even prices as more WAS are directed to the digester (increasing x). The break-even 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 | \(x = M_{n,10}/M_{a,1}\) (varied from 0 to 0.5)
3 | \(M_{n,10} = 126 + \text{WEIBULL}(1.42e+3, 2.74, N)\)
4 | \(M_{n,10} = 26 + \text{WEIBULL}(2.23e+3, 2.3, N)\)
5 | \(M_{e,a} = x \times M_{a,1}\)
6 | \(M_{e,n} = M_{e,n-1}\)
7 | \(M_{b,2} = M_{b,2} + M_{b,1}\)
8 | \(M_{g,7} = M_{g,7} + M_{g,6}\)
9 | \(M_{g,8} = M_{g,8} + M_{g,7}\)
10 | \(M_{g,9} = M_{g,9} + M_{g,8}\)
11 | \(M_{c,6} = M_{c,6} + M_{c,5}\)
12 | \(M_{c,7} = M_{c,7} + M_{c,6}\)
13 | \(M_{c,8} = M_{c,8} + M_{c,7}\)
14 | \(M_{c,9} = M_{c,9} + M_{c,8}\)
15 | \(M_{c,10} = M_{c,10} + M_{c,9}\)
16 | \(M_{c,11} = M_{c,11} \times (1 - X_{c,10})\times (M_{c,10} + M_{c,9})\)
17 | \(M_{c,12} = M_{c,12} \times M_{c,11}\)
18 | \(M_{c,13} = M_{c,13} \times M_{c,12}\)
19 | \(M_{c,14} = M_{c,14} \times M_{c,13}\)
20 | \(M_{c,15} = M_{c,15} \times M_{c,14}\)
21 | \(M_{c,16} = M_{c,16} \times M_{c,15}\)
22 | \(M_{c,17} = M_{c,17} \times M_{c,16}\)
23 | \(M_{c,18} = M_{c,18} \times M_{c,17}\)
24 | \(M_{c,19} = M_{c,19} \times M_{c,18}\)

\(M_{c,19}\) is mass flow rate (kg/day), \(x\) is the split mass fraction of WAS from stream 1 to stream 3

Table 3: Mass conversions algorithm.
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.

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

| Process               | Base Capacity and Capital Cost                                                                 | Base Cost Index (I)* |
|-----------------------|-------------------------------------------------------------------------------------------------|----------------------|
| 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% CH4 and 60-70% CO2) 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; pumps; heat exchangers; distillation columns for biodiesel recovery; recovery; heat exchangers; 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] | 325.3 (Year 1985) [24] |
| Trans-esterification  | Capacity: 3.07 × 106 gallons biodiesel/year [10], Size: Total Capital Cost: $490,000 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] |

*aAnnual 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]. bThis is the solids (activated sludge) retention time used in the fed-batch experiments [7]. cRevellame, Hernandez [9] found that moisture content less than 50% allows economical trans esterification of wet activated sludge.

Table 5: Utilities in the three technologies.

| 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]* | Generated in plant                        |
| Heat               | 1,330 kWh/Mt lipids [28] | Generated in plant                        |
|                    | Transesterification    |                                           |
| Electricity        | 3,116 kWh/Mt lipids*   | Generated in plant                        |
|                    |                        |                                           |
| MT: Metric Ton (1000 kg), 1 kWh=3.6 megajoules (MJ). *Includes electricity used for aeration, decanting, and pumping of streams [8]. 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 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     |                                           |
|                    | Simulated              | Generated in plant                        |
|                    | Simulated              | Generated in plant                        |
|                    | Simulated              | Generated in plant                        |
|                    | Transesterification    |                                           |
|                    | Simulated              | Generated in plant                        |
|                    | Simulated              | Generated in plant                        |
|                    | Simulated              | Generated in plant                        |
|                    | Methanol*              | $503/Mt [30]                             |
|                    | Sulfuric acid          | $750/Mt [31]                             |
|                    | Process water          | $0.05/Mt [28]                             |
|                    | Wash water             | Generated in plant                        |

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

| Product               | Price  |
|-----------------------|--------|
| Biodiesel             | $4.50/gal [29-32] |
| Biosolids             | $0.06/kg [4] |
| Electricity           | $0.11/kWh [33] |
| Waste sludge treatment| $0.045/kg [21] |

*Biodiesel density is 900 kg/m³ (3.41 kg/gal) [34]. *Pricing used was the average of the West South Central US region that includes Louisiana.

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

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

| 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 | 1,355 (497) | 1,355 (497) | 1,355 (497) | 1,355 (497) | 1,355 (497) | 1,355 (497) |
| PS, M_b  | 2,020 (905)  | 2,020 (905)  | 2,020 (905)  | 2,020 (905)  | 2,020 (905)  | 2,020 (905)  |
| Biogas, M_c | 484 (213) | 516 (215) | 548 (217) | 580 (220) | 612 (224) | 644 (228) |
| Biodiesel, M_d | 82 (32) | 77 (24) | 71 (22) | 65 (20) | 60 (18) | 55 (17) |
| Biosolids, M_e | 2,195 (661) | 2,128 (641) | 2,056 (622) | 1,987 (603) | 1,917 (584) | 1,848 (566) |
| 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_b,5 | 613 (274) | 656 (277) | 699 (280) | 742 (284) | 785 (289) | 828 (294) |
| M_c,6 | 206 (65) | 192 (60) | 178 (55) | 165 (51) | 151 (46) | 137 (41) |
| M_d,7 | 0 (0) | 135 (50) | 271 (99) | 407 (149) | 542 (199) | 677 (248) |
| M_e,8 | 2,030 (805) | 2,165 (912) | 2,301 (922) | 2,436 (934) | 2,572 (949) | 2,707 (966) |
| M_n,10 | 371 (164) | 391 (165) | 412 (167) | 432 (168) | 452 (170) | 472 (172) |
| M_m,11 | 2,030 (805) | 1,195 (465) | 1,268 (420) | 1,142 (374) | 1,015 (328) | 889 (283) |
| M_o,13 | 8.2 (2.6) | 7.7 (2.4) | 7.1 (2.2) | 6.6 (2) | 6.0 (1.8) | 5.5 (1.6) |
| M_n,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 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. Feedstocks                       |                 |                 |                 |                 |                 |
| Methanol                            | 1,63,800        | 1,62,771        | 1,61,654        | 1,60,488        | 1,58,700        | 1,57,896       |
| 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)       | 1,571 (2)$a$   |
| Process water                       | 27,661          | 26,745          | 25,806          | 24,892          | 23,420          | 23,037         |
| 2. Operating and maintenance        |                 |                 |                 |                 |                 |
| Labor (L)                           | 1,36,139        | 1,36,025        | 1,35,848        | 1,35,596        | 1,35,280        | 1,34,859       |
| Lab charges                         | 61,654          | 61,654          | 61,654          | 61,654          | 61,654          | 61,654         |
| Lab charges                         | 9,248           | 9,248           | 9,248           | 9,248           | 9,248           | 9,248          |
| Maintenance and repairs(MR)$a$      | 31,248          | 30,790          | 30,332          | 29,864          | 29,373          | 28,868         |
| Operating supplies$e$               | 8,509           | 8,494           | 8,471           | 8,438           | 8,397           | 8,342          |
| B. Indirect operating costs         |                 |                 |                 |                 |                 |
| Overhead (OH)$f$                    | 27,314          | 27,274          | 27,212          | 27,123          | 27,012          | 26,864         |
| Taxes$e$                            | 1,616           | 1,600           | 1,585           | 1,567           | 1,550           | 1,534          |
| Insurance$e$                        | 105,637         | 104,498         | 103,300         | 102,098         | 100,886         | 99,664         |
| C. Depreciation$g$                  |                 |                 |                 |                 |                 |
| D. General expenses$g$              |                 |                 |                 |                 |                 |
| Administrative expenses$g$          | 2,101           | 2,100           | 2,097           | 2,093           | 2,088           | 2,082          |
| Distribution and selling$g$         | 1,616           | 1,600           | 1,585           | 1,567           | 1,550           | 1,534          |
| D. Research and development$g$      | 105,637         | 104,498         | 103,300         | 102,098         | 100,886         | 99,664         |
| 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. *Annual usage in MT/year. 'Annual usage in x 1000 MT/year. *3 operators, 8-h shift per day, $24h, 15% of L, FCC=Capital cost1.15, 4% of FCC, 15% of MR+1.1% of MR+L, 1.5% of FCC, 0.5% of FCC, 0% of FCC, 25% of OH, 1% of SL, <4.8% of SL.
Table 12: Revenue 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: Metric Ton (=1000 kg).

Table 13: Energy accounting in the anaerobic digestion CHP system.
enhancement of WAS must be explored to achieve a feasible integration of this technology to anaerobic digestion and transesterification.

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Table 14: Profitability measures for the proposed 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) | n.a. | n.a. | n.a. |
| Breakeven biodiesel price ($/gal) | 11.949 | 11.963 | 12.134 |
| Breakeven biosolids price ($/kg) | 0.142 | 0.139 | 0.137 |
| Breakeven electricity price ($/kWh) | 0.209 | 0.195 | 0.184 |

x is the split mass fraction of WAS from stream 1 to stream 3. - Calculated only when the profit is positive; Equal to T CCP in years. “Calculated only when the profit is negative assuming ceteris paribus (Latin), meaning “holding other things constant”.

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