

EVALUATION OF AN ANAEROBIC SYSTEM FOR TREATING POULTRY MORTALITIES

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ABSTRACT. An anaerobic digestion system was evaluated as an alternative for poultry mortality disposal. The bench-scale system consisted of an upflow anaerobic sludge blanket (UASB) reactor and three leachbeds (LB). The LBs were batch-loaded with dead chickens and sequentially started at an average interval of 50 days. Only one LB was connected to the UASB to form a closed-loop at any one time. Leachate from the LB was fed to the UASB as influent while effluent from the UASB overflowed to the LB to maintain constant liquid volumes in both reactors. The LB-UASB pair initially functioned as a two-phase system, with the LB serving as the hydrolysis/acidification phase and the UASB serving as the methanogenic phase. Through repeated liquid recycle between the LB and the UASB, the LB eventually accumulated enough methanogens to become methanogenic as well. Leachate concentrations from the methanogenic LB dropped rapidly. When the leachate was no longer able to sustain the UASB at high loading rates (LR), the next LB with another dead chicken was connected to the UASB. Digestion of the mortality was considered complete when methane production rate from the off-line LB became marginal. When digestion in an LB was complete, the fermentation fluid in the LB was reused to start up the next LB. The first cycle ended when digestion in the third LB was complete. Two cycles were completed during this study. The system satisfactorily completed treatment of seven consecutive batches of mortalities in 432 days. The average CH_4 yield was $0.679 \text{ m}^3 \text{ (kg dry)}^{-1}$ [or $0.254 \text{ m}^3 \text{ (kg wet)}^{-1}$]. However, timings of the start-up of an LB and its subsequent connection to the UASB need to be improved to sustain the system at peak treatment efficiency. Alternatively, the system could include a fourth LB to allow more flexibility in scheduling. Additionally, a fifth LB reactor would simplify restarting of an LB from its preceding LB being terminated. Cost estimates based on systems with one UASB and five LBs ranged from US\$118 ($10^3 \text{ kg live wt sold}^{-1}$) for a 10,000 bird poultry farm to US\$28 ($10^3 \text{ kg live wt sold}^{-1}$) for a farm with 100,000 chickens.

Keywords. Poultry mortality, Anaerobic digestion, Leachbed, Upflow anaerobic sludge blanket, Leachate recycle, Cost estimate.

Proper disposal of mortality is crucial to sustaining animal industries, improving public health and protecting the environment. Anaerobic digestion has been proposed as an alternative to the conventional disposal methods of burial, incineration, rendering and aerobic composting (Chen and Shyu, 1998). The advantage of anaerobic digestion is that it couples waste treatment with methane production. In addition, the process inactivates pathogens (Lee and Shih, 1988; Shih, 1987). A closed-loop LB-UASB treatment system was found to initially function as a two-phase system, with the LB serving as the hydrolysis/acidification phase and the UASB serving as the methanogenesis phase (Chen and Shyu, 1998). Effluent from the UASB provides the LB with ungranulated methanogens. Through repeated liquid transfer between the UASB and the LB, the LB eventually accumulates enough methanogens to become a mature methane reactor. Unfortunately, the process was inefficient due to its batch-mode operation. It took 118 days to reduce 86% of the chemical oxygen demand (COD) of the

mortality (Chen and Wang, 1998). By successively connecting, then disconnecting, three LBs to a UASB to maintain the UASB at higher loading rates, treatment efficiency was much improved. It took 258 days to complete treatment of three consecutive batches of dead chickens (Chen, 1999). Longer-term operation to allow examination of the stability and operating strategy of the system is desirable. This manuscript shows results from continuous operation of the system for up to 432 days. This manuscript also discusses technical merits of the system and presents cost analyses.

MATERIALS AND METHODS

SYSTEM SETUP

The system consisted of one UASB and three LBs, but only one LB was paired with the UASB at any one time. Figure 1 shows the LB-UASB pair. The reactors were made of Plexiglas. The inside diameter of the UASB was 90 mm and that of the LB was 240 mm. The working volumes of the UASB and the LB were 3 and 10 L, respectively. Peristaltic pumps and Tygon tubing were used to circulate liquids in both reactors and to recycle leachate from the LB to the UASB. The UASB reactor was maintained at a constant temperature ($35 \pm 1^\circ\text{C}$) in a temperature-controlled chamber; whereas, the LB was kept at ambient temperatures. Biogas from each reactor was

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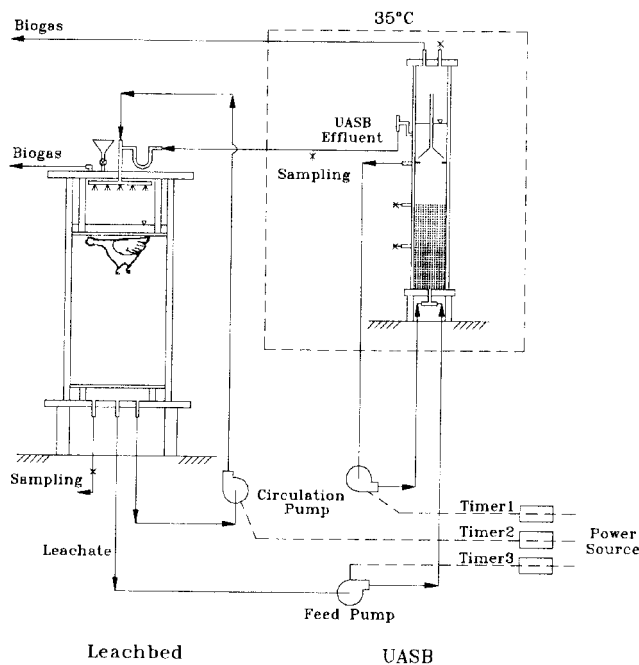


Figure 1—Schematics of an LB-UASB pair.

collected in a water displacement system. Duplicate systems were set up; hereafter designated systems A and B.

START-UP

The LBs were sequentially started. Each LB was started with a whole dead chicken obtained from the Poultry Farm at the National Chung-Hsing University in Taichung and 10 L of liquid. The average wet weight of the chickens was 1.5 kg. The liquid used in the first cycle consisted of between 5.5 and 8 L of supernatant from LBs that had been terminated for at least 17 days, and enough tapwater to make up the volume. Each LB in the second and third cycles was started from a terminating LB by replacing its undigested solids materials with another dead chicken. After closure, the LBs were flushed with O_2 -free N_2 gas at two times their void volumes. The UASB was started with about 50% (by volume) of granular sludge previously obtained from I-Lan Brewery Plant (Taiwan Tobacco and Wine Board, I-Lan).

OPERATION

The first cycle began when the first LB (LB-1) was connected to the UASB. Liquids in both reactors were circulated six times daily for 30 min each. Leachate from the LB was fed to the bottom of the UASB as influent while effluent from the UASB overflowed to the LB to maintain constant liquid volumes in both reactors. Flow rates through the reactors were determined by LRs to the UASB, which in turns, were a function of the leachate concentrations. Thus, the filtered COD (COD_f) of the leachate was monitored frequently and the data used to calculate flow rates needed to achieve the desired LRs to the UASB. Feeding of the UASB was started at $0.5 \text{ g } COD_f \text{ L}^{-1} \text{ day}^{-1}$ and raised in steps of $0.1 \text{ g } COD_f \text{ L}^{-1} \text{ day}^{-1}$ if COD reduction efficiency remained above 80% to avoid over-loading the UASB. When the LB entered the accelerated methanogenic phase, leachate CODs dropped

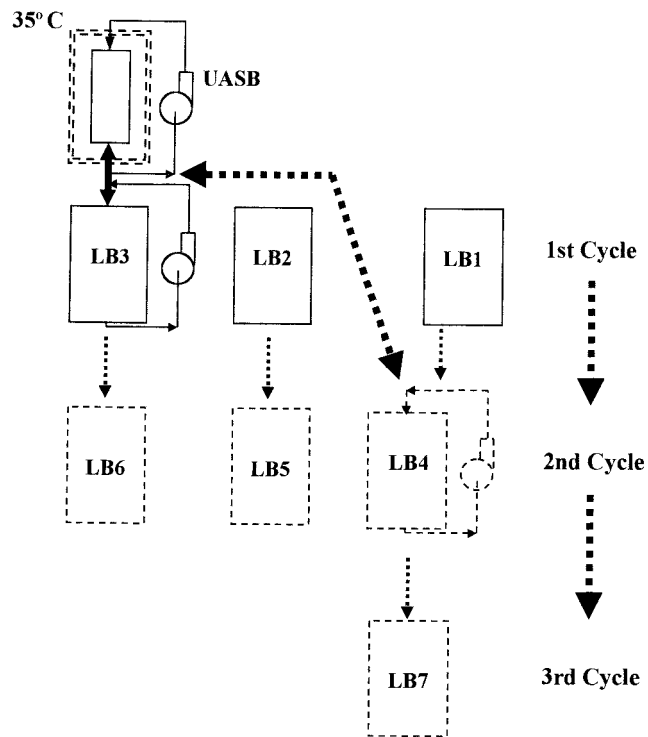


Figure 2—Diagram depicting the operating sequence of the system. Diagram shows when LB-3 is paired with the UASB while LB-1 and LB-2 are off-line. The dotted line with arrow ends indicates that LB-4 (restarted from the LB-1) will be paired with the UASB next to start the second cycle. The dotted lines with an arrow indicate that the LB-2 and the LB-3 will sequentially become LB-5 and LB-6, respectively, as the system progresses through its second cycle. Likewise, as the system enters its third cycle, the LB-4 will be restarted as LB-7, and so on.

rapidly (Chen, 1999). When its leachate concentrations could no longer sustain the UASB at the then highest LR of about $2.5 \text{ g } COD_f \text{ L}^{-1} \text{ day}^{-1}$, the LB-1 was replaced by a second LB (LB-2) containing another dead chicken. Operation of the new LB-UASB pair followed the same procedure as described above. The UASB moved on to a third LB (LB-3) when LB-2 entered the accelerated methanogenic phase and its leachate could no longer support active methanogenesis in the UASB. Digestion continued in the off-line LBs, without liquid circulation, until their methane production rates became marginal. Upon termination, LB-1 was restarted as LB-4 to begin the second cycle. Likewise, the third cycle began when LB-4 became LB-7 (fig. 2).

SAMPLING AND ANALYSES

Biogas composition was assayed with a thermal conductivity detector on a gas chromatograph (GC, Shimadzu GC-14A). Leachate from the LB and effluent from the UASB were analyzed periodically for total and volatile solids, pH, COD and volatile fatty acids (VFA). Solids and CODs were analyzed according to the Standard Methods (APHA, 1992). The CODs were determined colorimetrically. Both total COD (COD_t) and COD_f were measured. Samples for COD_f analyses were filtered through Supor®-450 filters (Gelman Sci., Ann Arbor, Mich.). The difference between COD_t and COD_f was taken to be sludge. The VFAs were determined with a flame

ionization detector on a GC (Hitachi 5000A, Japan) as previously described (Chen and Wang, 1998).

BUDGET ESTIMATES

Detailed specifications of treatment systems for poultry farms of sizes up to 100,000 chickens were drawn up based on experimental results reported herein. Budget estimates were derived following prevailing pricing practices. Cost elements considered included labor, capital investment and operation costs, as well as indirect costs such as maintenance, taxes, insurance, and administrative costs. Capital investments were amortized over 10 years at an annual interest rate of 10%. It was assumed that the farmers own the land and the system requires a part-time operator. No by-products credit was given.

RESULTS

LEACHED PERFORMANCE

Digestion in the LBs can be divided into three phases. The first phase was characterized by a lag period. This phase lasted for about 80 days for LBs in the first cycle and was under 20 days for LBs in the second cycle (fig. 3). The materials in the LBs initially underwent hydrolysis and acidification, causing rapid rises in leachate COD and a drop in pH. In some cases, total volatile fatty acids (TVA) were as high as 20 g L^{-1} (fig. 4), contributing up to 90% of the leachate CODs. Methane appeared in LB-1, LB-2 and LB-3 25, 20, and 6 days, respectively, after their start-ups (fig. 5). In contrast, subsequent leachbeds that inherited the whole fermentation fluid of freshly terminated LBs began methane production on the same day they were started. Methane content in biogas gradually increased as the LBs were maturing. The LBs entered the second phase when methane contents in biogas stabilized at above 75%.

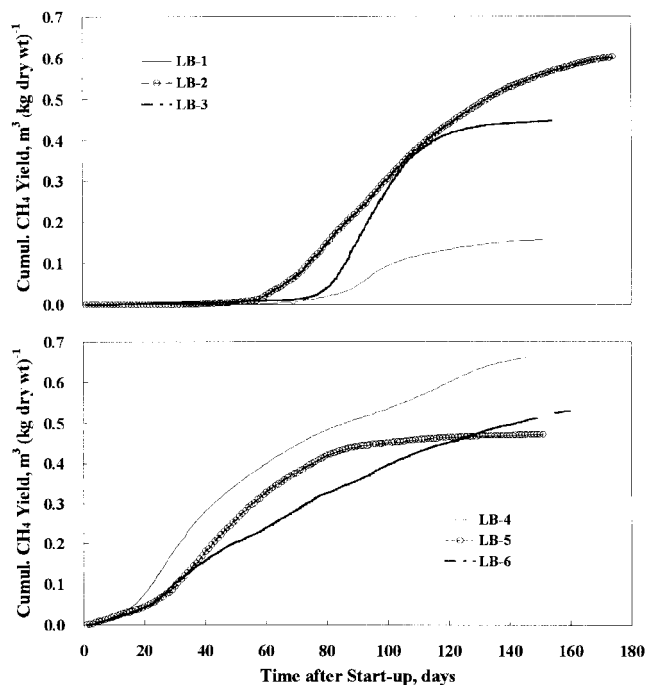


Figure 3—Cumulative CH_4 yields from the LBs, showing typical digestion pattern of a lag followed by accelerated and then decelerated methanogenesis.

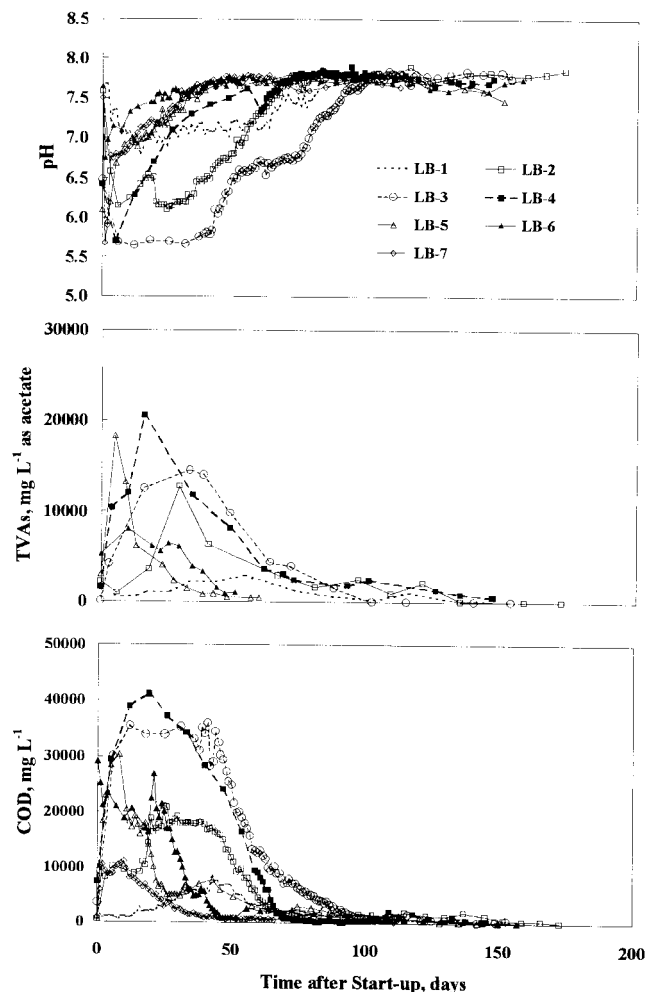


Figure 4—Chemical characteristics of leachbed leachate.

Methane production rates increased rapidly and peaked during this phase. It took an average of 93 days for LBs in the first cycle to reach these peaks while those in the following cycles took 27 days (fig. 6). It also appeared that methanogenesis was affected by ambient temperatures. Peak methane production rates reached 8 to 10 L day^{-1} during the summer months. Those for the winter months were much lower, at around 1.5 to 2 L day^{-1} (fig. 7). The third phase started when leachate CODs dropped below 1 g L^{-1} and CH_4 production rates slid below half their peaks. Cumulative methane yields started to level off (fig. 3). The LBs were terminated when their methane production rates became marginal. When the LBs were terminated, leachate CODs had dropped below 0.5 g L^{-1} and each LB had been operated for an average of 156 days. On average, 175 grams (dry weight) of bones and feathers remained in each LB.

UASB PERFORMANCE

Since leachate from a connected LB was fed undiluted to the UASB, influent concentrations to the UASB varied due to continuously changing leachate concentrations (fig. 4), as well as sequential connections to the next LBs (fig. 8). Influent COD_f concentrations ranged between $36\,000$ and 90 mg L^{-1} for UASB-A, and that for UASB-B were between $45\,000$ and 80 mg L^{-1} . Furthermore, since

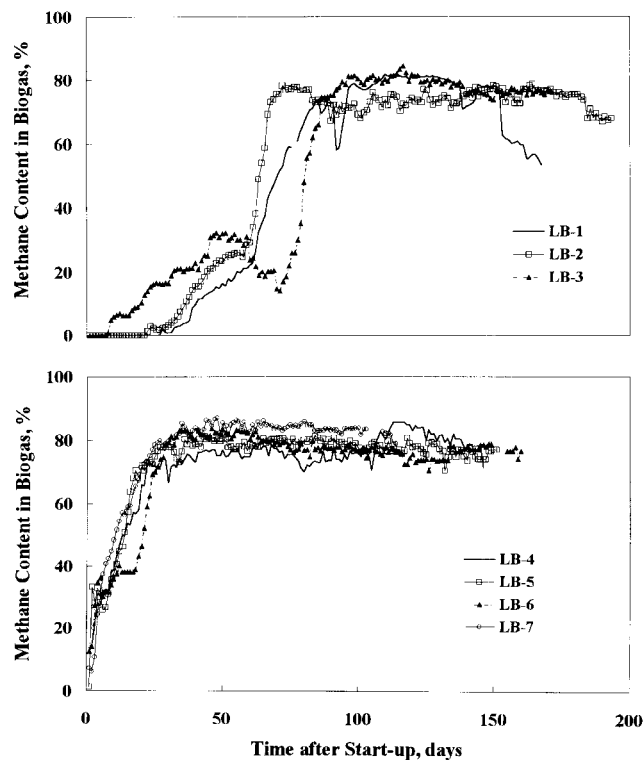


Figure 5—Methane content of biogas from the leachbeds. Leachbeds in the second (LB-4, LB-5, and LB-6) and third (LB-7) cycles started producing methane sooner than LBs in the first cycle (LB-1, LB-2, and LB-3).

the operational strategy was to raise LRs incrementally, it was therefore necessary to adjust flow rates through the reactors frequently. Flow rates through the reactors ranged between 78 and 14 000 mL day⁻¹. Consequently, hydraulic retention times (HRT) for the UASBs varied between 38 and 0.21 days. An attempt was made to maintain a minimum HRT of 0.25 day for the UASBs to avoid excessive washout of their granular sludge.

Loading rates generally rose during the first six months of operation, reaching as high as 6.3 g COD_f L⁻¹ day⁻¹ (fig. 8). Between days 175 and 195, the LRs were in a range above 5 g COD_f L⁻¹ day⁻¹. This LR was comparable to the 11 g COD L⁻¹ day⁻¹ achieved in treating slaughterhouse wastewater using a granular sludge UASB reactor (Sayed et al., 1987) since the ratio between COD_f and COD_t of the influent in this study was less than 0.5 during this period (fig. 9). However, loading rates in this study did not remain at that level as connection of LB-4s and start-ups of subsequent LBs were delayed. Loading rates fell below 0.5 g COD_f L⁻¹ day⁻¹ before rising again. Operation of the UASBs was stopped after 359 days when LB-7s were disconnected. Overall, LRs to the UASBs averaged 2.9 g COD_f L⁻¹ day⁻¹. In spite of the varying influent CODs and LRs, the UASBs performed very well at all times. Their effluent TVA concentrations were low throughout the experiment, with an average of 0.28 g as acetate per liter (fig. 10). Methane production rates followed the LRs closely (figs. 8 and 10), indicating that methanogenesis was stable and not rate-limiting. By comparison, Chen and Shyu (1998) reported deteriorating treatment efficiencies when LR was raised from 2 to 5 g

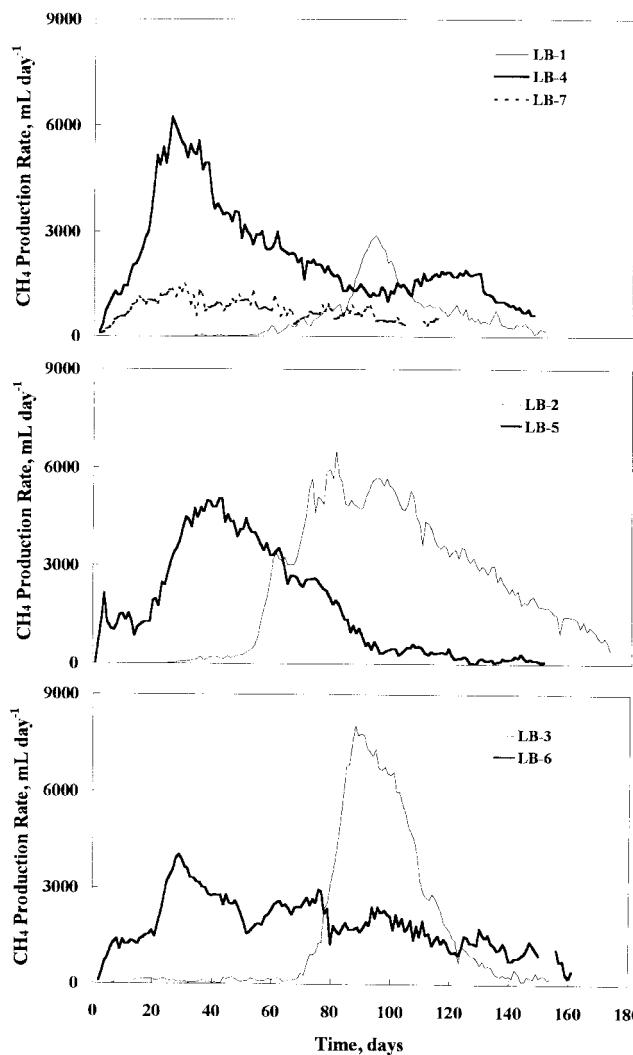


Figure 6—Time to peak methane production rates. Methane production rates peaked around day 93 for LB-1, LB-2, and LB-3 (from the first cycle), day 27 for LB-4, LB-5, and LB-6 (from the second cycle), and LB-7 (from the third cycle).

COD_t L⁻¹ day⁻¹ at 0.2 g COD_t L⁻¹ day⁻¹ incrementally. Consequently, careful increments of LRs seemed important to the satisfactory performance of the UASBs in this system.

SYSTEM PERFORMANCE

System methane production consisted of methane produced from the UASB and all the LBs of each system. As LBs were sequentially started, each system included one UASB and one, two, then three LBs. Thus, system methane production rate gradually increased as more LBs became operational. They peaked at 21 L day⁻¹ for system A and 19 L day⁻¹ for system B. The peak methane production rates were equivalent to COD removal rates of 1.8 and 1.6 g COD L⁻¹ day⁻¹ for systems A and B, respectively. Stable methane production rates could not be maintained however, due to failure to schedule LB start-ups so that gas production from each LB would complement that of others. When all LBs were terminated on day 432, the system had completed treatment of seven consecutive batches of dead chickens. System A produced

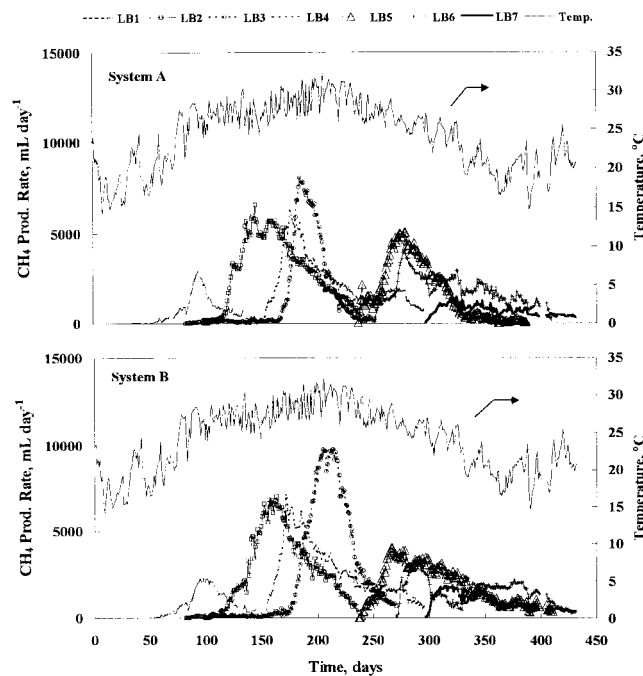


Figure 7—Temperatures and methane production rates from the LBs.

a total of 2.55 m³ of methane and system B produced 2.86 m³, with respective methane yields of 0.671 and 0.687 m³ (kg dry)⁻¹ [or 0.251 and 0.257 m³ (kg wet)⁻¹]. On average, 68.9% of the total methane from each system came from the LBs.

DISCUSSION

With low pH and very high VFAs (fig. 4), early environments in the LBs were not conducive to methanogenesis. Additionally, the supernatant used to start-up LBs in the first cycle contained very little solids. Thus, these LBs depended on methanogens carried over by effluent from the UASB to start producing methane. Leachate recycle was considered key to successful implementation of a similar system, the sequencing batch reactor system, treating municipal solid waste (Chynoweth et al., 1991; Nopharatana et al., 1998). Leachate was recycled through matured leachbed reactors in that system instead of UASB as in this study. The LB-3 started producing methane earlier than preceding LBs (fig. 5), probably benefiting from warmer temperatures and increasingly more active biomass received from the UASB due to increasingly higher LR. The LB-1, LB-2, and LB-3 were started on days 0, 63, and 98, respectively, as the temperatures were gradually increasing (fig. 7). However, methane production rates from LBs in the first cycle remained low until each had accumulated about 30 g of sludge from its respective UASB. By comparison, Chen and Wang (1998) found their LBs needed about 100 g of flocculent sludge from the connecting UASB to start active methanogenesis. The difference in the amounts of sludge needed to begin active methane production could probably be attributed to differences between methanogenic activities of the accumulated sludges.

It took two to three months for LBs in the first cycle to mature. In contrast, LBs in the following cycles entered the

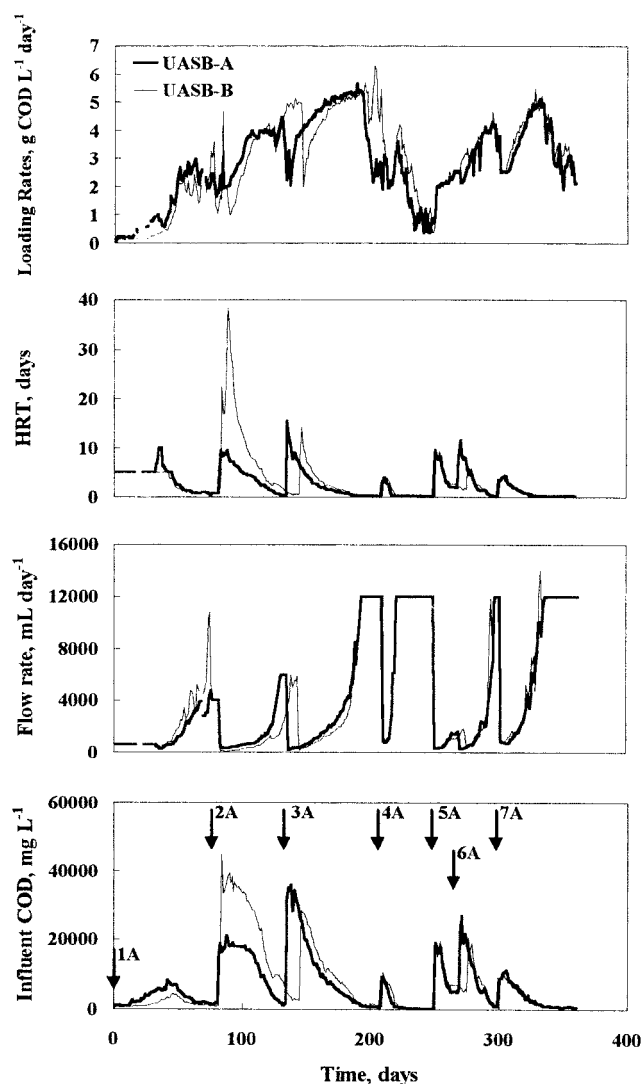


Figure 8—Operating conditions for the UASBs. Arrows denote sequential connections of UASB-A to the indicated LB on day 0, 82, 135, 209, 250, 270, and 300, respectively. The UASB-B was sequentially connected to its corresponding LB on day 0, 82, 145, 209, 250, 275, and 300, respectively.

accelerated methanogenic phase within 30 days after their start-ups (fig. 5), before significant accumulation of methanogenic sludge from the UASB. In particular, LB-4 matured before even being connected to the UASB (fig. 11). Apparently, the fermentation fluid in a would-be-terminated LB contained enough microbes and associated enzymes for independent start-up and maturation of the subsequent LB. Hence, while the UASB was the source of methanogens for LBs in the first cycle, microbes needed by LBs in following cycles were inherited from terminating LBs. Consequently, the UASB may be necessary only for LBs in the first cycle. It may even be possible that a UASB is not needed at all if sufficient inocula, not necessarily granular sludge, could be obtained.

From the standpoint of biogas utilization, it is desirable to maintain the system at a state of stable and high methane production. To achieve this goal, timings of the start-up of an LB and its subsequent connection to the UASB are important (Chen, 1999). However, this requires careful

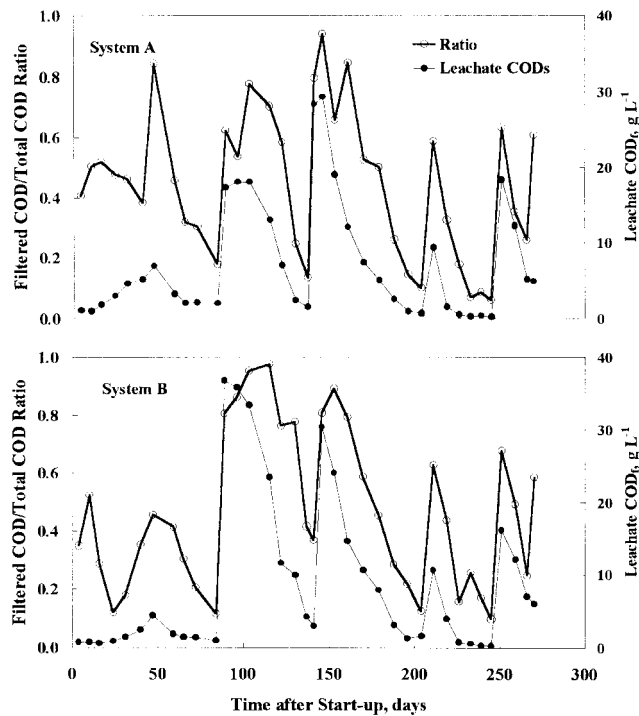


Figure 9—Temporal profile of the ratio of filtered COD to total COD of leachbed leachate.

monitoring of leachate CODs. It may also dictate an irregular start-up schedule since LB reactors will become reusable at variable intervals as digestion in some LBs will be completed faster than in others due to variations in chicken sizes and ambient temperatures. Thus, the troubles of a complicated scheduling effort might outweigh its benefits. For the sake of operational simplicity, it would be more convenient to schedule start-ups on fixed intervals. Therefore, a fourth LB reactor is necessary in order to accommodate variations in digestion processes throughout the year.

The procedure of replacing the remaining solids from a terminating LB with another batch of dead chickens may be cumbersome in a large reactor. To facilitate restarting of a terminated LB, thus, further simplifying operation of this system, there could be a fifth LB reactor. When fermentation in the first LB is complete, instead of removing the remaining solids from the wet LB-1, liquid in it can be pumped into the fifth reactor to start the second cycle. The resultant de-watered LB-1 should make removing the residual solids easier. Table 1 outlines events that will occur during three complete cycles of continuous operation of such a system with one UASB and five LBs. However, there will always be one de-watered LB after the system becomes fully operational. The LB reactors will take turns becoming the de-watered LB as the system progresses from one cycle to the next.

In reality, it might not be necessary to remove the remaining solids after each batch since only a small fraction of dead chickens would remain undigested. For a 1.5 kg chicken, the 175 g residual solids occupied less than 5% of the digester volume. The reactor could easily be reused without removing the remains until, for instance 20%, of the volume has been occupied. Thus, removal of the residual solids from each LB may be needed only once

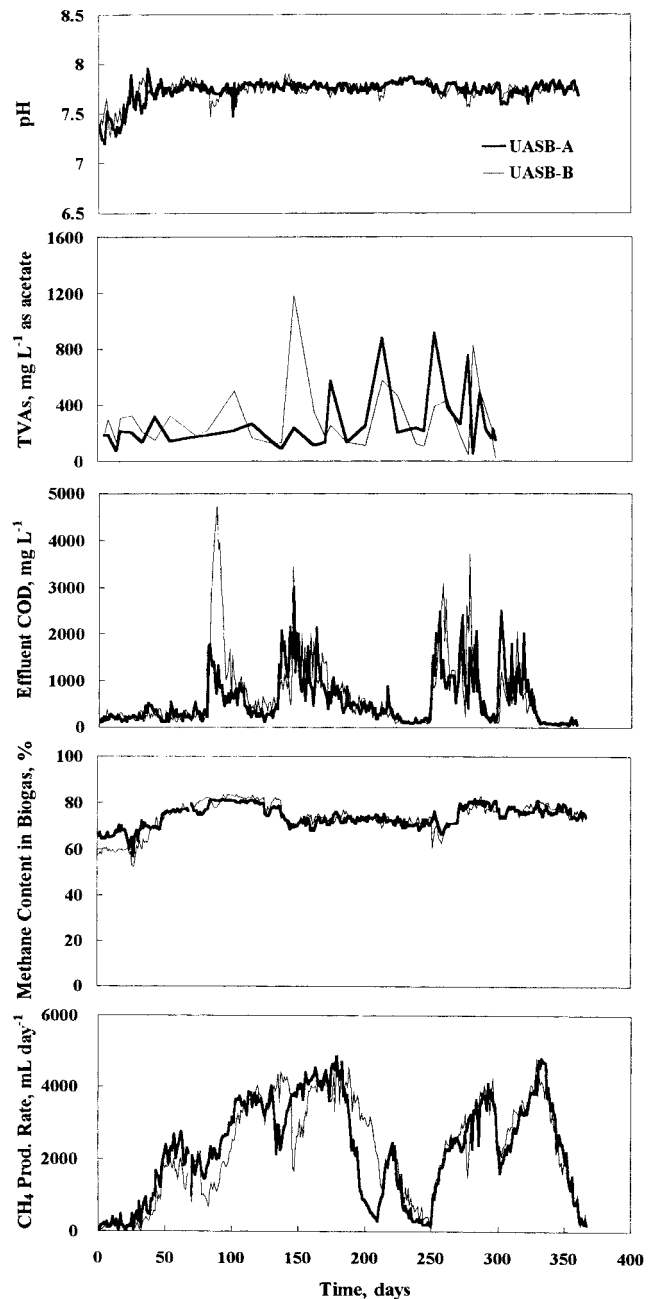


Figure 10—Performance of the UASBs.

a year or less frequently. By that time, the remains of each chicken could be less than 175 g due to further degradation of bones and feathers. Although no microbiological study was conducted in this study, survival of pathogens in this system is expected to be limited. Many factors in an anaerobic digester, such as absence of oxygen, VFAs, and ammonia might be lethal to pathogens. Lee and Shih (1988) found that the oocysts of *Eimeria tenella*, one of the common and economically devastating pathogens in poultry, were 90 to 99% inactivated after only five days in a 35°C digester treating poultry waste. With prolonged fermentation such as occurred in this study, the survival rate could decline further. Since the fermentation fluid in a terminated LB is reused to start-up the next LB, there would be no wastewater disposal problem during

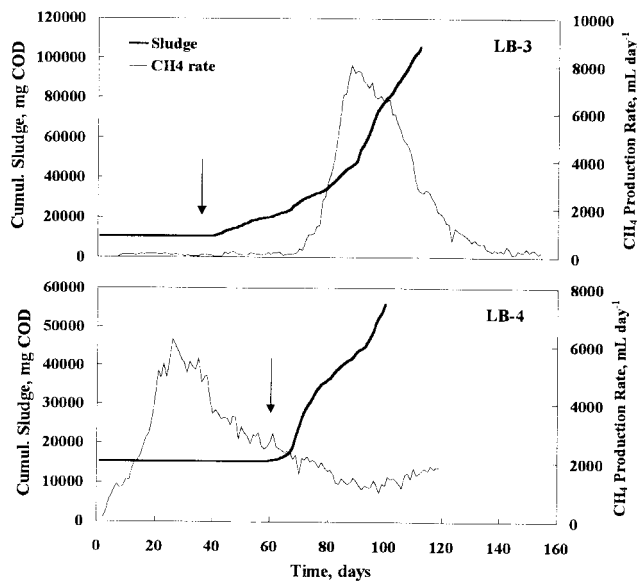


Figure 11—Relationships between accumulation of sludge in the LBs and methane production rates from the LBs. Arrows indicate when each LB was connected to its corresponding UASB.

continuous operation of the system. Thus, the process is technically competitive with another commonly accepted biological treatment alternative: the composting process (Blake and Donald, 1992). Furthermore, the 62-day average time it took to treat one batch of dead chickens is comparable to the composting process. Thus, considering its treatment efficiency and methane production, the system should be a viable alternative to other treatment methods. Since it requires minimum routine operation, it would be especially suitable for poultry farms where the labor force is small and a dedicated operator would be unavailable.

Budget analyses were based on systems with one UASB and five LBs as prescribed above. With each reactor 4 m in depth, a treatment system for a 10,000-chick poultry farm

Table 2. Summary of cost analyses of the LB-UASB system* for treating mortalities for a 10,000-bird poultry farm

Cost Element	Annual Cost (US\$)	
	Scenario 1†	Scenario 2§
Capital	4741	4953
Maintenance	129	155
Utility	588	634
Labor#	6237	6409
Total	11,694	12,150
Annual poultry production		
Birds (@ 1.8 kg avg)	60,000	70,000
Live wt sold** (kg)	99,360	115,920
Average cost per 10 ³ kg live wt sold	118	105

* A system with one UASB and five LBs was assumed. The reactors were constructed of reinforced concrete.
 † Assumed production of six batches of chickens per year.
 § Assumed production of seven batches of chickens per year.
 || Assumed 10-year amortization at an annual interest rate of 10%.
 # Assumed a part-time operator.
 ** Chickens are sold in Taiwan based on live weight. Assumed a mortality rate of 8%.

required an area of 3.5 m × 4.5 m. The cost to a poultry operation with 10,000 birds was estimated to be US\$118 (10³ kg live wt sold)⁻¹ or US\$105 (10³ kg live wt sold)⁻¹ depending on whether six or seven batches of chickens were raised per year (table 2). These cost figures represent between 9 and 10% of the wholesale price of chickens in Taiwan. Capital costs were about 41% of annual expenditure. There were economies of scale. As the farm size increased, the costs decreased to about US\$28 (10³ kg live wt sold)⁻¹ for a 100,000 bird operation (fig. 12). The economics could improve further when credit from methane is considered.

CONCLUSIONS

The anaerobic system with one UASB and three LBs performed satisfactorily. Reusing the fermentation fluid from a terminating LB facilitated the start-up and maturation of subsequent LB as well as eliminated

Table 1. Events* occurring during continuous treatment of poultry mortality in the proposed anaerobic system with one UASB and five LBs

Time Period	Leachbed Reactor				
	1st Reactor	2nd Reactor	3rd Reactor	4th Reactor	5th Reactor
First cycle					
1	Starts LB-1, connecting				
2	Disconnecting				
3	↓	Starts LB-2, connecting			
4	Completing	Disconnecting			
5	↓	↓	Starts LB-3, connecting		
6	Emptying	Completing	Disconnecting		
7	Starts LB-6, connecting	Emptying		Starts LB-4, connecting	
8	Disconnecting	Starts LB-7, connecting		Disconnecting	Starts LB-5, connecting
9	↓	Disconnecting		Completing	Disconnecting
10	Completing	↓	Starts LB-8, connecting	Emptying	Completing
11	Emptying	Completing		Starts LB-9, connecting	Emptying
12	Starts LB-11, connecting	Emptying	Disconnecting	Disconnecting	Starts LB-10, connecting
13	Disconnecting	Starts LB-12, connecting	Emptying	Completing	Disconnecting
Fourth cycle					
14	↓	Disconnecting	Starts LB-13, connecting	Emptying	Completing

* Connecting means that the LB is to be connected to the UASB during this period. Disconnecting means that the LB is to be disconnected from the UASB during this period. The off-line LB will complete digestion independently. Completing means that digestion of mortality in the LB is to be completed during this period. Emptying means that fermentation fluid in the LB is to be pumped to a new LB appearing on the same row during this period. For example: during period 10, fermentation fluid in the 1st reactor (then LB-6) is to be pumped to the 5th reactor that is to be started up as LB-10. Residual solids in the de-watered LB-6 can be removed, if necessary.

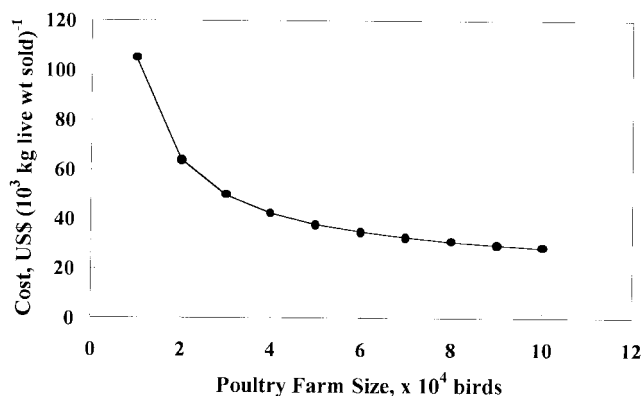


Figure 12—Estimated cost of the anaerobic mortality treatment system as a function of farm sizes.

wastewater disposal problems. It took an average of 62 days to treat one batch of mortality. The average methane yield was $0.679 \text{ m}^3 (\text{kg dry})^{-1}$ [or $0.254 \text{ m}^3 (\text{kg wet})^{-1}$]. However, timings of the start-up of an LB and its subsequent connection to the UASB need to be improved to sustain the system at peak treatment efficiency. Alternatively, the system could include a fourth LB to allow more flexibility in scheduling. Additionally, a fifth LB reactor could simplify restarting of an LB from its preceding LB being terminated. Cost estimates based on systems with one UASB and five LBs ranged from US\$118 ($10^3 \text{ kg live wt sold})^{-1}$ for a 10,000 bird poultry farm to US\$28 ($10^3 \text{ kg live wt sold})^{-1}$ for a farm with 100,000 chickens.

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