Clean Techn Environ Policy
DOI 10.1007/s10098-009-0228-1

ORIGINAL PAPER

EMMC technology for treatment/reuse of dilute dairy wastewater

Rhoda Luo-Ting Lin · Joshua Lelemia Irvine · J. C. M. Kao · P. Y. Yang

Received: 21 August 2008 / Accepted: 13 April 2009

Abstract A rural dairy farm located on the island of Oahu, Hawaii needed to upgrade current lagoon treatment system for further reuse as floor flushing and crop irrigation. This is a comprehensive bench scale and pilot plant study to evaluate the potential biological treatment and reuse systems. Systems evaluated include: (1) pre-existing lagoon system, (2) integrated anaerobic BIO-NEST/aerobic EMMC (entrapped mixed microbial cell) system, (3) aerobic EMMC reactor only system. Based upon a comprehensive economic evaluation and sensitivity analysis, the EMMC-only system achieved the best effluent quality for simultaneous removal of carbon and nitrogen. The pilot study of the EMMC-only reactor achieved an overall of 78% TCOD, 63% SCOD, 65% TN, and 96% soluble NH_3-N removal efficiencies (HRT 12 h, continuous aeration). Implementing this system would cost about \$0.25 a cow/day to remove a ton of organic TCOD (\$88.10/cow/year). The information presented provides a model for animal producers to consider in evaluating alternatives to upgrade existing waste management facilities.

Keywords Dilute dairy wastewater · Entrapped mixed microbial cell · Treated wastewater reuse · Carbon and nitrogen removal · Treatment alternatives · Economic evaluation

R. L.-T. Lin · J. L. Irvine · P. Y. Yang (✉)
Graduate Program in Bioengineering, Department of Molecular Biosciences and Bioengineering, University of Hawaii at Manoa, Honolulu, HI 96822, USA
e-mail: pingyi@hawaii.edu

J. C. M. Kao
Graduate Institute of Environmental Engineering, National Sun Yat-San University, Kaohsiung, Taiwan

Introduction

Anaerobic lagoon systems have been widely used to manage dairy wastewater throughout the United States because it is simple, and provides feasible and non-technical operation/maintenance. However, major disadvantages of implementing lagoon systems include ineffective biological removal of nutrients—especially total nitrogen removal (Bolan et al. 2004); difficulty to remove stabilized solids from the lagoon when full; potential risks of leakages and wastewater seepage into the soil (Metcalf and Eddy 2003; Grady et al. 1999). More importantly, lagoon systems may be inappropriate for areas that are land limited like the islands of Hawai'i because of the large space required for lagoon installation (Kongsil 2006).

A rural dairy farm located on the island of Oahu, Hawaii needed to upgrade their current lagoon treatment system. The original wastewater treatment system at the dairy farm used two facultative lagoons. Each lagoon had dimensions of 76.2 m × 15.2 m × 18.3 m. The hydraulic retention time of each lagoon to treat the dairy wastewater was 3.6 days. The farm received lagoon treated wastewater from 10 acres of irrigated land planted with California grass (*Brachiaria mutica*). Also, the composting facilities existed on the farm (Dong 2003; Kongsil 2006). These two treatment facilities can be integrated (lagoon and composting) with other renovation/reuse processes to provide greater removal of organics and nitrogen of the diary wastewater. The farm planned to later use the treated effluent for floor washing and crop irrigation.

There is no strict reuse standard for the flushing of milk parlor facilities in the United States. However, an acceptable TSS concentration of <5 mg/l and BOD_5 <20 mg/l is recommended for reuse of treated domestic wastewater (Crook and Surampalli 1996). In order to meet requirements

Published online: 01 May 2009

Table 1 New treatment target criteria

Category	TCOD	Nitrogen (TN)	Phosphorous (P)	SS	Effluent pH
Target concentration	650–700 mg/l	70–80 mg/l	6–10 mg/l	5–8 mg/l	6.5–8.5
Target reduction efficiency	85–90%	60–65%	50–70%	97–99%	

Source: Dong (2003)

for agriculture practices and reuses a target quality criteria for the treated are presented in Table 1 (Dong 2003).

To achieve the proposed target criteria, it is recommended that integrating the current dairy farm wastewater treatment process with EMMC technology and it needs to be further investigated. A comprehensive bench scale and pilot plant study evaluated the potential renovation and reuse designs and operation. Systems evaluated include: (1) pre-existing lagoon system, (2) integrated anaerobic BIO-NEST/aerobic EMMC system, (3) aerobic EMMC reactor only system.

Laboratory and pilot scales were conducted to characterize the process performance. Furthermore, the effectiveness of the various treatment alternatives was compared on the basis of achieving target water quality discharge, and economic feasibility. Bench scale testing of EMMC later determined the optimal HRT, aeration condition, and packing ratio. The results from the laboratory investigation were replicated at the pilot scale.

A comprehensive economical evaluation and sensitivity analysis of the field investigation findings were made. All this information combined can be used to assist the Dairy Farm to select the best system design and operation to meet the objectives of treatment and reuse.

Methods

Potential treatment alternatives

Various potential biological treatment alternatives were proposed to determine the most effective renovation and reuse system to meet the Dairy Farm's needs. The following criteria were used as a comparison basis: loading rate, organic removal efficiency, nitrogen removal, and water discharge quality to evaluate the most effective renovation alternative.

Outlined below are the treatment alternatives evaluated:

Option 1:

$$\text{Settling} \rightarrow \text{Anaerobic BIO} - \text{NEST} \rightarrow \text{Aerobic EMMC system} \rightarrow \text{Existing Lagoon} \rightarrow \text{Reuse}$$

Option 2:

$$\text{Settling} \rightarrow \text{Anaerobic BIO} - \text{NEST} \rightarrow \text{Aerobic EMMC system} \rightarrow \text{Existing Lagoon} \rightarrow \text{Reuse}$$

Option 3:

$$\text{Settling} \rightarrow \text{Aerobic EMMC} \rightarrow \text{Lagoon} \rightarrow \text{Reuse (with existing lagoon and new composting facility)}$$

Option 4:

$$\text{Settling} \rightarrow \text{Aerobic EMMC} \rightarrow \text{Lagoon} \rightarrow \text{Reuse (with existing lagoon and composting facility)}$$

Option 5:

$$\text{Settling} \rightarrow \text{Existing Lagoon} \rightarrow \text{Aerobic EMMC} \rightarrow \text{Reuse}$$

Option 6:

$$\text{Solid/liquid separator} \rightarrow \text{Aerobic EMMC} \rightarrow \text{Existing Lagoon} \rightarrow \text{Reuse}$$

Wastewater characteristics

The dairy farm at the time used two existing facultative lagoon systems as treatment method. In this study two separate pilot scale experimental runs (Fig. 1) tested pre-treated anaerobic wastewater (PTAW) and settled raw wastewater (SRW) as influent to evaluate EMMC process performance. This was to determine the potential process performance of integrated systems and EMMC reactor-only treatment. The SRW characteristics with and without settlings is presented in Tables 2 and 3.

The operation conditions of PTAW (integrated systems treatment process) and SRW (EMMC only treatment process) for both laboratory and pilot plant scales are summarized in Tables 4, 5, 6, and 7.

EMMC carrier preparation

The modified EMMC carriers were prepared by modifying the carrier using a plastic biobarrel as the "frame;" thus, eliminating the step of shape-cutting previously used (Yang and See 1991). The preparation process and

Fig. 1 Pilot plant layout (*Source*: Kongsil 2006)

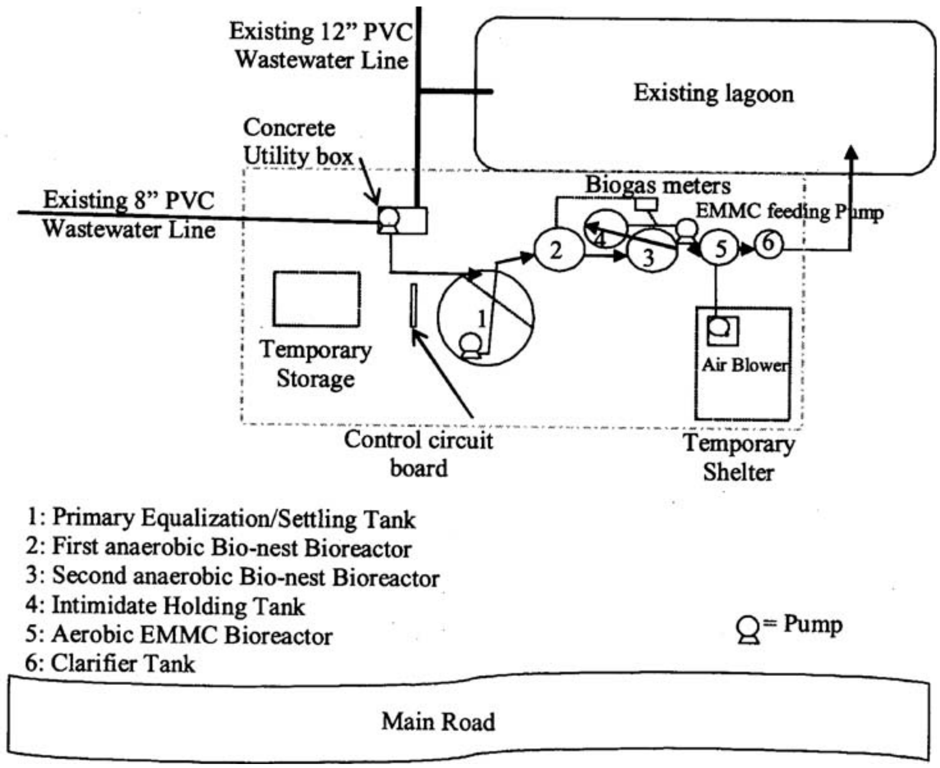

Table 2 Characteristic of milk parlor wastewater (mg/l)

	TCOD	SCOD	TN	NH_3-N	TSS	pH
Influent concentration	3993.2 ± 1568.7	811.6 ± 258.5	173.8 ± 49.14	61.8 ± 38.2	3875.25 ± 1782	6.8–9.4
Sample size	12	12	5	6	12	12

Table 3 Characteristic of milk parlor wastewater after settling in the main holding tank

	TCOD	SCOD	TN	NH_3-N	TSS
Wastewater concentration	1412.3 ± 505	362 ± 106	237.6 ± 58.8	128.4 ± 30.5	1,256 ± 763
Sample size	38	38	20	14	34

Table 4 Operation conditions for pre-treated anaerobic treated wastewater influent (Laboratory Study)

Packing ratio	10%	15%
Influent source	After anaerobic Bionest treatment	
Total volume	4,800 ml	
Void volume	4,320 ml	4,080 ml
Temperature	Ambient temperature (about 2–25°C)	
pH	6.82–8.21	
Influent TCOD (mg/l)	334–823	
SCOD (mg/l)	143–536	
TN (mg/l)	110–260	
Aeration	Intermittent, 1 h on and off	
HRT	6, 8, 12, and 24 h	

Table 5 Operation conditions for settled raw wastewater influent (Laboratory Study)

Packing ratio	10%	15%
Influent source	Raw wastewater	
Total volume	4,800 ml	
Void volume	4,320 ml	4,080 ml
Temperature	Ambient temperature (about 20–25°C)	
pH	7.13–8.07	
Influent TCOD (mg/l)	855–4230	
SCOD (mg/l)	212–952	
TN (mg/l)	99–166	
Aeration	Continuous	
HRT	12 and 24 h	

Table 6 Operation conditions for pre-treated anaerobic wastewater influent (Pilot Plant Study)

Packing ratio	12.5%
Influent source	After anaerobic Bionest treatment
Liquid volume	1,000 gallons (3.8 m^3)
Temperature	Ambient temperature (about 20–25°C)
Influent TCOD (mg/l)	285–1,885
SCOD (mg/l)	197–342
TN (mg/l)	148–350

Table 7 Operation conditions for settled raw wastewater influent (Pilot Plant Study)

Packing ratio	12.5%
Influent source	Raw wastewater
Liquid volume	1,000 gallons (3.8 m^3)
Temperature	Ambient temperature (about 20–25°C)
Influent TCOD (mg/l)	249–3,345
SCOD (mg/l)	142–321
TN (mg/l)	91–318

modified EMMC carriers are presented in Figs. 2 and 3, respectively. Based on our past 20 years of EMMC studies, they do not show any negative effect for the killing of bacterial cell through the toluene hardening process.

EMMC and BIO-NEST reactors

Two EMMC reactors were installed in the lab each reactor had a carrier-volume packing ratio of 10 and 15% (Fig. 4).

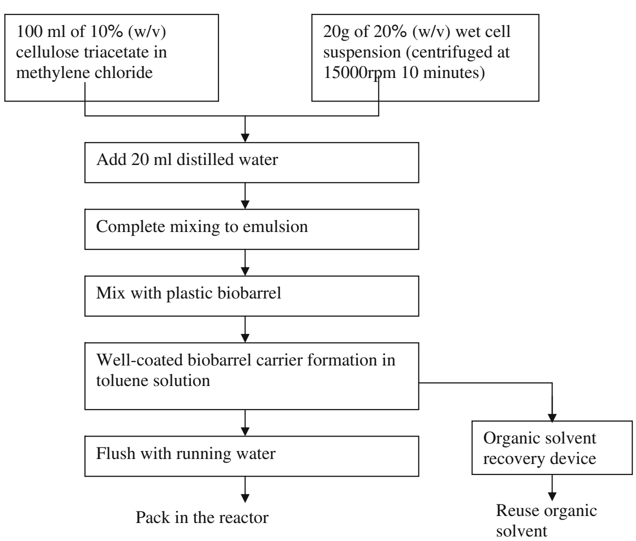

Fig. 2 EMMC carrier making process

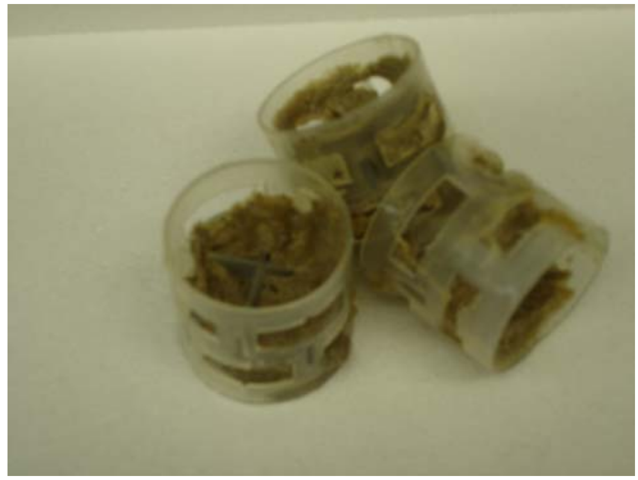

Fig. 3 Modified EMMC carriers

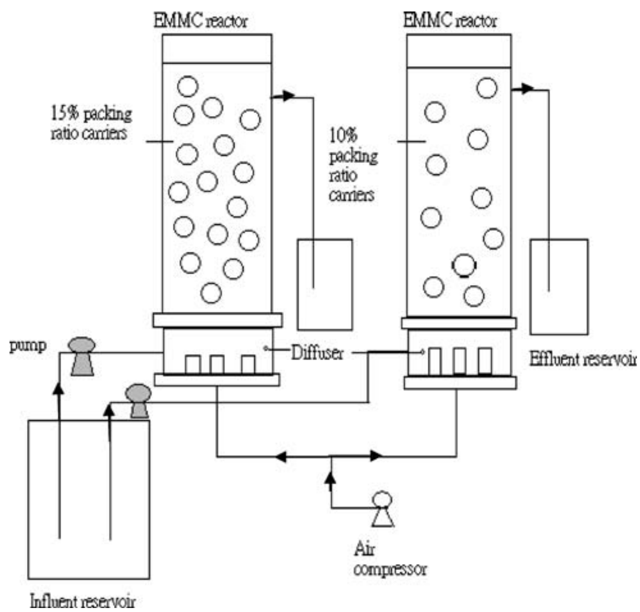

Fig. 4 EMMC reactors

The total liquid volume of each reactor was measured to be 4,800 ml. The media volume at 10% packing ratio reactor with 4,320 ml liquid in reactor and the media volume of the 15% packing ratio reactor with 4,080 ml liquid in reactor. The influent was mixed in a reservoir and fed to each reactor. Water flowed from the bottom of the reactor and exited at the top of the reactor. Air diffusers were installed at the bottom and aeration was supplied by an air compressor at a flow rate of 1.25 L per L of reactor volume per min. Two BIO-NEST 10 m^3 sized reactors were used. The operation conditions for the EMMC units in the laboratory are shown in Table 8.

Table 8 Different packing ratio, HRT, and aeration condition conducted in the lab

Packing ratio (%)	HRT (h)	Aeration condition
10	24	Continuous
	12	Continuous
		1 h on, 1 h off
		1 h on, 2 h off
	8	Continuous
		1 h on, 1 h off
	6	Continuous
15	12	Continuous
		1 h on, 1 h off
		1 h on, 2 h off
	8	Continuous
		1 h on, 1 h off
	6	Continuous

Chemical analysis

Influent and effluent samples were measured to evaluate the water quality and overall effectiveness of the treatment process. Samples in the lab were taken from the influent reservoir and supernatant of an effluent reservoir three times a week. Samples in the pilot plant were withdrawn in the intermittent holding tank, clarifier tank, and lagoon two to three times a week (refer to parts 4, 6, and existing lagoon from Fig. 4, respectively). Chemical analysis include: TS (Total Solid), TSS (Total Suspended Solid), TVS (Total Volatile Solid), TVSS (Total Volatile Suspended Solid), TCOD (Total Chemical Oxygen Demand), SCOD (Soluble COD), TN (Total Nitrogen), NH_3-N, and pH. The TS, TSS, TVS, TVSS, TCOD, SCOD, TN, NH_3-N analyses were conducted according to the Standard Methods (APHA 1989). The pH was measured using the Orion 501 pH meter.

Results and discussion

A comprehensive bench scale and pilot plant study evaluated the potential renovation and reuse design and operation. Systems evaluated include: (1) pre-existing lagoon system, (2) integrated anaerobic BIO-NEST/aerobic EMMC system, (3) aerobic EMMC reactor only system.

Pre-existing lagoon system treatment

The analysis of this lagoon operation for effluent quality (No. of samples 18) indicated an average effluent TCOD concentration of 1,183.9 mg/l and SCOD of 206.6 mg/l. The average TN concentration was observed to be 148.6 mg/l and the average NH_3-N concentration was 108.3 mg/l (Table 9).

The results reveal that the lagoon is capable of achieving a TCOD, SCOD, and TN removal of 74.6, 72, and 16.5, respectively. However, under the operation of a hydraulic retention time of 3.6 days, the NH_3-N concentration actually increased. It is clear that the TN and NH_3-N removal performance is poor and there is a need to integrate the existing facility with further biological treatment process for nitrogen removal in order to meet the reuse criteria as suggested in Table 1.

Process performance for the lab scale

Bench scale testing of EMMC was used to determine the optimal operation condition for carbon and nitrogen removals. It was found that at a HRT of 12 h, continuous aeration, and packing ratio of 15% provided the best simultaneous removal of carbon and nitrogen when using raw wastewater influent (Lin 2007).

These optimal operational criteria were used to compare the process performance for PTAW and SRW (Table 10; Figs. 5, 6). The TN removal efficiency of using SRW influent rather than PTAW is better.

The major contributor for improved TN removal in SRW influent is due to the COD to N ratio. The reaction of denitrification requires a carbon source:

$$NO_3^- + \underbrace{0.833CH_3OH}_{\text{(CARBON SOURCE)}} \rightarrow 0.5N_2 + 0.833CO_2 + 1.167H_2O + OH^-$$

From the above chemical balance, 1.9 g of methanol is needed to reduce 1 g NO_3-N.

An insufficient carbon source quantity is the main cause for poor denitrification which leads to diminish total nitrogen removal. Yang et al. (2001) evaluated the direct removal of nitrate with Entrapped Mixed Microbial Cell Technology using ethanol as a carbon source. When the COD/N ratio is more than 7, it was observed that a COD

Table 9 Lagoon process performance

	TCOD	SCOD	TN	NH_3-N
Influent (mg/l)	3993.2 ± 1568.7	811.6 ± 258.5	173.8 ± 49.14	61.8 ± 38.2
Effluent (mg/l)	1183.9 ± 1138.9	206.6 ± 51.2	148.6 ± 67.7	108.3 ± 34.4
Removal (%)	74.6	72	*16.5*	*–120.7*

Table 10 Comparison between pre-treated anaerobic and raw wastewater influents with packing ratio 15%, HRT 12 h, and continuous aeration

	Sample size	Removal efficiency (%)				Effluent quality (mg/l)			
		TCOD	SCOD	TN	NH_3-N	TCOD	SCOD	TN	NH_3-N
Anaerobically treated influent	12	72.66	60.18	*27*	95.6	265.58 ± 111	193.5 ± 57	*106*	4.5 ± 0.57
Raw wastewater influent	5	78	63	*65*	96	250 ± 128	146 ± 14	*44*	2 ± 1
P value						0.86	0.01	*0.003*	0.02
Significant						No	Yes	*Yes*	Yes

Significance: 0.025 critical value: ±2.048

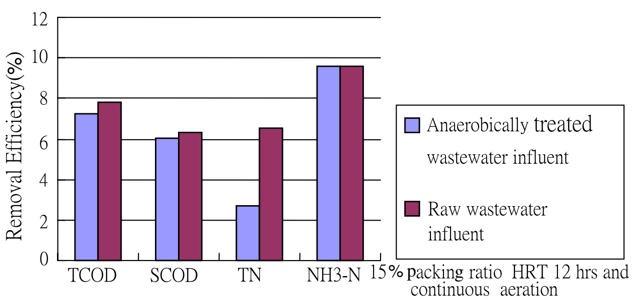

Fig. 5 Comparison between pre-treated anaerobic wastewater influent and settled raw wastewater influent in removal efficiency (Laboratory)

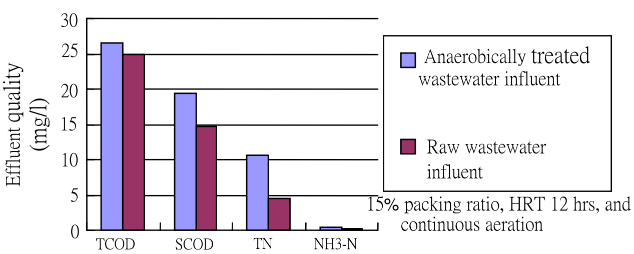

Fig. 6 Comparison between pre-treated anaerobic wastewater influent and raw wastewater influent in effluent quality (Laboratory)

removal of greater than 80% and the nitrate removal greater than 94% can be achieved. At COD/N ratios ranging between 5 and 8, nitrate and COD removal efficiencies of greater than 90 and 80%, respectively, can be achieved.

Another study by Yang et al. (2002a, b) investigated applying the EMMC process in combined secondary and tertiary wastewater treatment. The study showed that nitrogen removal efficiencies increased as the carbon to nitrogen ratio increased. Likewise, investigations conducted by Watanabe et al. (1992) confirmed that simultaneous nitrification and denitrification (SND) in RBC (Rotating Biological Contactors) also is strongly influenced by the wastewater *C*/*N* ratio. At a *C*/*N* ratio of 6, the maximum nitrogen removal efficiency can be achieved. In this study, the *C*/*N* ratio for PTAW influent was 5.3 and SRW influent 10–15.6. Consequently, the denitrification for nitrate removal requires higher *C*/*N* ratio.

Process performance for pilot scale

The pilot plant reactor installation and operating conditions are presented in Fig. 1, and Tables 6, 7. Evaluating the process performances of the option 1 and 2 (Table 11) and option 3 and 4 (Table 12) demonstrates that EMMC reactor-only system out performs the integrated treatment system in overall total nitrogen removal (Tables 11, 12; Figs. 7, 8). The influent wastewater characteristics for Tables 11 and 12 are varied because the sampling dates correlate to the operating the milk parlor facilities.

Among the combined Bio-NEST/EMMC, EMMC reactor-only, and lagoon only alternatives process, the EMMC reactor-only alternative has the best effluent quality and removal efficiency (Table 13, Fig. 9).

The EMMC reactor-only technology developed at the University of Hawaii is a state of the art biological treatment/renovation process for the simultaneous removal of carbon and nitrogen as well as provides a simple design operation compared to activated sludge process and other aerobic biological treatment unit processes (Yang et al. 1997, 2002a, b, 2003; Song et al. 2006; Cho et al. 2007).

It is therefore, that the EMMC technology investigated in this study was used to evaluate the impact of effluent

Table 11 Field operation performance of EMMC from the pre-treated anaerobic wastewater effluent

Parameters indicated	TCOD	SCOD	TN	NH_3-N
Influent to EMMC reactor (mg/l)	452.4 ± 141.7	226.2 ± 32.4	179.4 ± 20.9	152.7 ± 11.3
Effluent (mg/l)	306.5 ± 92	176.6 ± 35.7	130 ± 21.9	59.7 ± 44.8
Average removal (%)	38.4	26.7	30.2	68
Sample size	14	14	9	9

Table 12 Pilot scale EMMC process with raw wastewater influent

	TCOD	SCOD	TN	NH_3-N
Influent (mg/l)	1143.8 ± 1184.9	263 ± 65.2	214.5 ± 89.3	124.9 ± 29.8
Effluent (mg/l)	271.7 ± 120.8	186.5 ± 54.1	87.2 ± 15.8	53 ± 25.8
Average removal (%)	61.5	28.3	53.1	54.9

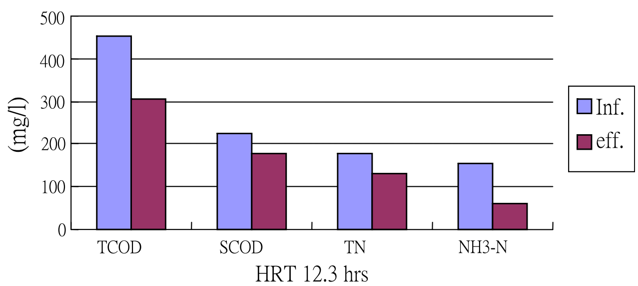

Fig. 7 Pilot scale EMMC process performance with HRT 12.3 h for the pre-treated anaerobic effluent

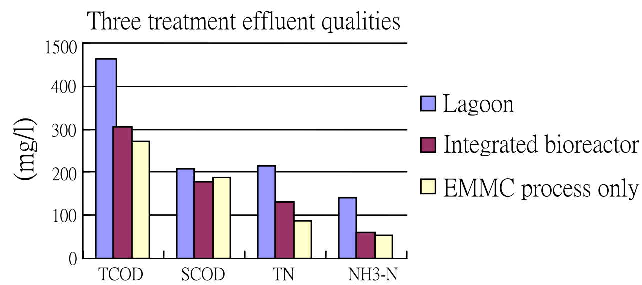

Fig. 9 Comparison of the effluent quality among three treatment alternatives. (Average value)

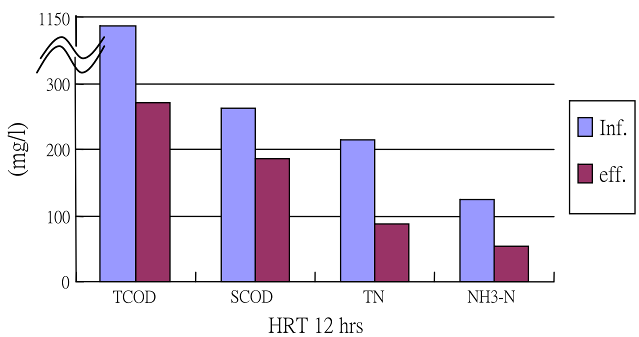

Fig. 8 Pilot scale EMMC process performances with raw wastewater influent. (Average value)

Table 14 The cost per dairy cow per year for dilute wastewater

Treatment	Cost per dairy cow per year
Option 1	$90.52
Option 2	$101.67
Option 3	$76.22
Option 4	$68.62
Option 5	$58.5
Option 6	$82.79

quality and cost analysis in order to observe the impact of EMMC technology on the effluent from the system, three treatment alternatives were compared. They were combined Bio-nest and EMMC, EMMC reactor-only, and lagoon system only. As shown in Table 14 and Fig. 9, the EMMC reactor-only alternative has the best effluent quality and removal efficiency. Thus, the EMMC reactor-only option could solve the deficient nitrogen removals by lagoon system only and combined anaerobic bioreactor and EMMC system. Furthermore, a solid/liquid pretreatment unit process integrated with EMMC bioreactor and the existing lagoon system is capable of achieving floor flushing water and irrigation criteria as suggested in Table 1 for the proposed treatment target criteria. It is expected that the integrating existing lagoon system will improve the removal of listed target concentration and meet the reuse treated wastewater criteria.

Table 13 Effluent quality for the three treatment alternatives

Treated alternative	HRT	TCOD	SCOD	TN	NH_3-N
Influent, mg/l		1401.2	358.4	232.6	128.4
Lagoon effluent, mg/l	3.6 days	1183.9	206.6	216.1	139.8
Integrated bioreactors (anaerobic plus EMMC bioreactors) effluent, mg/l	19.83 h (main holding tank) 22.2 h (anaerobic) 12.3 h (aerobic)	306.5	176.6	130	59.7
EMMC process only eff., mg/l	12 h	271.7	186.5	87.2	53

Potential treatment alternatives and economic evaluation

One of the full-scale dairy farms in the State of Hawai'i operates at a capacity of 960 cows. A full-scale economic evaluation of the existing dairy farm accessed the six options at full capacity was evaluated by Lin (2007) and is presented in Table 14. The evaluation took into account construction costs, operational and maintenance, and benefits from biogas production, reuse and composting.

The effluent quality of these six options were evaluated (Lin 2007) and is presented in Table 15. Apparently, the options 1, 3, and 4 are able to meet the proposed target effluent criteria for TCOD and BOD_5 discharge standards as shown in Table 1. Options 3 and 4 achieved the best effluent total nitrogen concentration—nearly meeting target concentration goals (Table 1). However, option five yielded the lowest cost overall in operational cost: \$58.5/cow/year. Also, more importantly, options three and four provided higher effluent quality for organic and total nitrogen removal than all other options. Furthermore, a sensitivity analysis with an interest rate of 0 and 10% supplemented with an economic evaluation was conducted and is presented in Fig. 10. The combined economic and sensitivity evaluations show that option four is the most optimal alternative to achieve project goals.

Table 15 Effluent quality of these six options

(mg/l)	TCOD	BOD_5	SCOD	TSS	TN	NH_3-N
Option 1	306.5	73.37	176.6	161	130	59.7
Option 2	828.27	285.5	529.24	N/A	134.18	N/A
Option 3	271.7	59.2	186.5	N/A	87.2	53
Option 4	271.7	59.2	186.5	N/A	87.2	53
Option 5	449.9	131.67	262.9	N/A	89.8	N/A
Option 6	463.31	137	268.65	N/A	91.87	N/A

Conclusion

A local dairy farm needed to upgrade its current lagoon wastewater treatment system to utilize an untapped resource. The comparison study evaluated various renovation and reuse system designs to treat the wastewater generated by the Dairy Farm. At full-scale operation 960 cows are processed daily.

The alternative treatment system designs proposed include: (1) Pre-existing lagoon treatment, (2) Integrated anaerobic BIO-NEST/aerobic EMMC treatment and (3) EMMC-only reactor treatment. In this study, bench scale and pilot scale systems of the designs evaluated the process performance of each treatment process. Based upon this information combined with an economic and sensitivity analysis confirms that EMMC-only reactor treatment (option four) is the most efficient and effective treatment.

The EMMC-only system achieved simultaneous of removal carbon and nitrogen as well as low TSS discharge. The proposed EMMC-only design includes: (1) solid/liquid separation of dairy wastewater, (2) the solids will be transferred to an existing compositing facility, (3) the dilute liquid portion would be applied to the aerobic EMMC reactor. It is also recommended that the existing lagoon be integrated with EMMC to improve the final effluent quality. The dairy farms plans to reuse the effluent for floor flushing and crop irrigation of California grass.

The recommend system design also provides economic benefits for the dairy farm because the farm will be able to produce composting product recovered from separated solids. The revenue generated would further reduce overall operational and maintenance cost. It would only cost less than \$0.25 a cow/day to remove a ton of organic TCOD (\$88.10/cow/year). The results and analysis provide a management guideline for animal producers interested in upgrading pre-existing wastewater treatment systems. More importantly, this can be an addition model for regulatory agencies to consider in establishing effluent renovation and reuse to efficiently protect receding bodies of water and the environment.

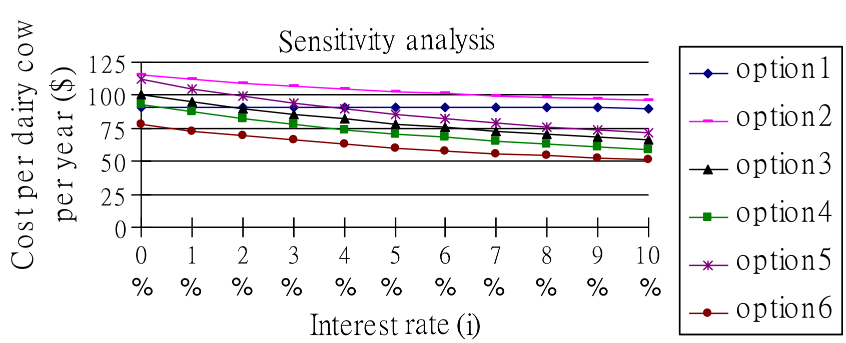

Fig. 10 Sensitivity graph of interest rate for the six options proposed

Acknowledgments This project was funded by the USDA-TSTAR program and DOA of the State of Hawaii with the College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa. National Sun Yat-Sun University in Taiwan provided the visiting Fellowship for Dr. P. Y. Yang during the period of the preparation of this manuscript.

References

Bolan NS, Wong L, Adriano DC (2004) Nutrient removal from farm effluents. Bioresour Technol 94(3):251–260

Cho ES, Zhu J, Yang PY (2007) Intermittently aerated EMMC-Biobarrel (Entrapped Mixed Microbial Cell with Bio-barrel) process for concurrent organic and nitrogen removal. J Environ Manage 84:257–265

Crook J, Surampalli RY (1996) Water reclamation and reuse criteria in the US. Water Sci Technol 33(10–11):451–462

Dong L (2003) An integrated treatment and reuse system of dairy wastewater—a case study in the state of Hawaii. MS Thesis, University of Hawaii at Manoa, Honolulu, HI, p 58

Grady CPL Jr, Daigger GT, Lim HC (1999) Biological wastewater treatment, 2nd edn. CRC, Taylor & Francis Group, New York

Kongsil P (2006) Engineering and economic evaluation of innovative bioreactor for milk parlor wastewater treatment/reuse. MS Thesis, University of Hawaii at Manoa, Honolulu, HI, p 216

Lin L-T (2007) Comparison of different technologies for dilute milk parlor wastewater treatment and reuse. MS Thesis, University of Hawaii at Manoa, Honolulu, HI, p 120

Metcalf JS, Eddy FB (2003) Wastewater engineering treatment and reuse, 4th edn. McGraw Hill, Boston

Song C, Cho ES, Yang PY (2006) Removal of organic and nitrogen and molecular weight distribution of residual organic from EMMC (Entrapped Mixed Microbial Cells) and activated sludge process. Water Environ Res 78:2501

Watanabe Y, Matsuda S, Ishiguro M (1992) Simultaneous nitrification and denitrification in micro-aerobic biofilms. Water Sci Technol 26(3–4):511–522

Yang PY, See TS (1991) Packed-entrapped microbial cell process for removal of phenol and its compounds. J Environ Sci Health A 26(8):1491–1512

Yang PY, Zhang ZQ, Jeong BG (1997) Simultaneous removal of carbon and tropical application. Water Res 31:2617–2625

Yang PY, Qian X, Maekawa T (2001) Evaluation of direct removal of nitrate with entrapped mixed microbial cell technology using ethanol as the carbon source. Water Environ Res 73(5):584–589

Yang PY, Cao K, Kim SJ (2002a) Entrapped mixed microbial cell process for combined secondary and tertiary wastewater treatment. Water Environ Res 74(3):226–234

Yang PY, Shimabukuro M, Kim SJ (2002b) A Pilot scale bioreactor using EMMC for carbon and nitrogen removal. Clean Technol Environ Policy 3:407–412

Yang PY, Su R, Kim SJ (2003) EMMC process for combined removal of organics, nitrogen, and odor producing substance. J Environ Manage 69:381–389