

# TREATMENT OF HIGH-CONCENTRATION SWINE WASTEWATER BY ANAEROBIC DIGESTION AND AN AQUATIC PLANT SYSTEM

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**Abstract** : The treatment of high-strength swine wastewater by anaerobic digestion combined with an aquatic plant system was investigated. Anaerobic digestion of swine wastewater gave volatile solids (VS) removal efficiencies of 43.3%, 52.1% and 54.5% for hydraulic retention times (HRTs) of 20, 30, 40 days, respectively. The removal efficiencies of VS, total chemical oxygen demand (TCOD) and soluble chemical oxygen demand (SCOD) decreased with increasing VS volumetric loading rate (VLR). Higher organic removal efficiency was observed at longer HRTs for the same VS volumetric loading rate. As VS volumetric loading rate increased, biogas production increased and the methane content of the biogas decreased. Experiments using duckweed (*Lemna species*) as an aquatic macrophyte gave the following results. In the case of nitrogen, removal efficiency was above 60% and effluent concentration was below 10.0 mg/L when the influent ammonia-N loading was about 1.0 g/m<sup>2</sup>/day. In the case of phosphorus, removal efficiency was above 55% and effluent concentration was below 2.0 mg/L when the influent PO<sub>4</sub>-P loading was about 0.15 g/m<sup>2</sup>/day. In addition, crude protein and phosphorus content of duckweed biomass increased from 15.6% to 41.6% and from 0.8% to 1.6%, respectively, as the influent nutrient concentration increased. The treatment of high-strength swine wastewater by anaerobic digestion combined with an aquatic plant system offers good performance in terms of organics and nutrient removal for relatively low operation and maintenance costs. The results indicate that under appropriate operational conditions, the effluent quality is within the limits set by Korean discharge criteria.

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**Key Words** : Anaerobic Digestion, Aquatic Plants System, Methane Production Rate, Duckweed(*Lemna Species*), Growth Characteristics, Crude Protein

## INTRODUCTION

To date, research into how to deal with large quantities of highly polluted swine waste is concentrated on wastewaters composed of small quantities of excreta, urine and wash water from cement type swine sheds.<sup>1-2)</sup> In contrast, little research has been conducted on slurry wastewaters from net-type swine sheds.<sup>3)</sup>

In the treatment of slurry type swine wastewater, the high solids content makes it necessary to first separate out the solids and then to apply anaerobic processes such as UBF, UASB and AAFEB to the effluent. These anaerobic processes have been previously used to degrade organic compounds in high strength organic wastewaters,<sup>4-5)</sup> however, other process is required to treat the separated solids.<sup>6-7)</sup>

The use of aquatic plants to treat wastewater is an economical method that can remove not only nutrients but also highly concentrated organics,

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as well as significant amounts of refractory organic trace matter. Moreover, studies have shown that aquatic plants used for wastewater treatment can be subsequently utilized as protein sources, in methane production, and as animal feed.<sup>8-9)</sup>

For many years, water hyacinths have been used for wastewater treatment under good climatic conditions, these floating aquatic plants effectively remove nitrogen and phosphorus.<sup>10)</sup> However, these plants are not useful in low temperature.<sup>11)</sup> The utility of hyacinths is also limited by difficulty in harvesting and processing.<sup>12)</sup> In contrast, it has been reported that another floating aquatic plant, duckweed, is generally less sensitive to temperature and easier to gather than water hyacinth. In addition to this, it has very high specific growth rates (0.1~0.5 day<sup>-1</sup>). Moreover, duckweed selectively absorbs NH<sub>3</sub>-N,<sup>13-14)</sup> giving it an outstanding ability to remove a major pollutant in swine wastewater.

The present study sought to determine the efficacy of treating swine wastewater containing high strength solids with anaerobic digestion followed by duckweed treatment. Anaerobic digestion was carried out in a completely mixing anaerobic digester that was selected due to its ease of operation for the treatment of swine waste containing high strength solids. In addition, the nutrient removal and growth characteristics of duckweed were characterized according to the influent loading variations.

## EXPERIMENT

### Experimental Equipment and Materials

The anaerobic digester was made of an acrylic cylinder (inside diameter 280 mm, thickness 10 mm), and four acrylic pipes of diameter 20 mm were attached to the reactor for input and output of samples.<sup>3)</sup>

A Direct Driven Stirrer (YOUNG JI Precision System; 0~110 rpm) was used as the mixing motor; it was operated at 30 rpm for complete mixing. Anaerobic sludge from the Chun cheon municipal wastewater treatment plant in Korea was used for initial seeding. A glass beaker

(volume 1 L, water surface area 86.6 cm<sup>2</sup>) was used for the pilot treatment device. The outside wall of the beaker was covered with aluminum foil to limit the growth of algae which may inhibit the growth of duckweed. The *Lemna gibba* used in the experiments was gathered from a paddy field near Toe-gae dong, Chun cheon city, Gang won Do, Korea. The color of the duckweed fronds was dark-green and the root length was approximately 10 mm. Table 1 shows the characteristics of the influent wastewater that was treated in the experiments by anaerobic digestion and aquatic plants. The substrate injected into the anaerobic digester was obtained from a 1000-head swine shed located in Chun cheon city, Korea. The substrate was sampled two times per week.

The aquatic plant treatment was implemented as follows. The effluent from the anaerobic digester was settled for 12 hours in Imhoff cone to remove the effect of solids, and the supernatant was diluted with tap water.

Table 1. Characteristics of influent wastewater.  
(unit: mg/L, except where indicated)

Parameters	Anaerobic Digestion	Parameters	Aquatic Plant System
pH	6.4 - 8.2	pH	6.47 - 8.10
Temp.(°C)	35±1	Temp.(°C)	24.9 - 33.2
TS	28,460 - 77,620	TP	0.48 - 19.33
VS	21,460 - 60,920	PO <sub>4</sub> -P	0.28 - 11.02
TCOD	38,211 - 84,950	TCOD	7.6 - 723.0
SCOD	3,995 - 13,275	SCOD	4.5 - 428.5
TKN	1,401 - 3,315	TKN	2.2 - 87.4
NH <sub>4</sub> -N	503 - 1,286	NH <sub>4</sub> -N	1.7 - 66.9

Abbreviations:

TS: Total solids

VS: Volatile solids

TKN: Total Kjeldahl nitrogen

TP: Total phosphorus

TCOD: Total chemical oxygen demand

SCOD: Soluble chemical oxygen demand

### Operation and Analysis Method

The anaerobic digester was operated as a semi-continuous fed and completely mixed reactor (SCFMR), with input and output once every 3 days. Hydraulic retention times (HRTs) of 20, 30, and 40 days were used; these values were

selected due to the high solids content of the substrates used in this study. The effective volume of the digester was 22 L. Influent and effluent quantities for each of the HRTs were 1.1 L/day at 20 days, 0.73 L/day at 30 days, and 0.55 L/day at 40 days.

In the aquatic plant treatment experiment, sufficient duckweed was cultivated to cover the entire water surface (7.12 g/m<sup>2</sup> as dry mass [DM]). The HRT was fixed at 3 days on the basis of the findings of Oron,<sup>9)</sup> who reported that the growth rate and protein content in tissue were excellent at HRT 3 days when duckweed was used to treat raw sewage. We observed the characteristics of nutrient removal and duckweed growth at various swine wastewater concentrations up to the maximum concentration at which duckweed is able to grow. The experiments were conducted in batch mode.

The harvest time of the grown duckweed depends on the specific growth rate (SGR) of each reactor. Harvesting was performed in such a way that sufficient duckweed was retained to form a mat on the effluent surface. The SGR and doubling time of duckweed were calculated as follows:

$$\text{SGR} = \ln(W_t / W_o) / t \quad (1)$$

$$D_t = \ln 2 / \text{SGR} \quad (2)$$

where, SGR : specific growth rate (day<sup>-1</sup>)

W<sub>o</sub> : quantity of duckweed at beginning of cultivation (g)

W<sub>t</sub> : quantity of duckweed after t days of cultivation (g)

t : duration of cultivation (days)

D<sub>t</sub> : doubling time

The Monod equation was used to calculate the maximum SGR and the half-velocity constant K<sub>s</sub> value according to the substrate concentration.<sup>15)</sup> To calculate the maximum SGR and K<sub>s</sub> value a nonlinear regression model (Jandel Scientific) was used. The Monod formula is as follows.

$$\mu = \mu_{\max}(S/(S+K_s)) \quad (3)$$

where, μ : specific growth rate coefficient (day<sup>-1</sup>)

μ<sub>max</sub> : maximum specific growth rate (day<sup>-1</sup>)

S : concentration of growth-limiting substrate in solution (mg/L)

K<sub>s</sub> : half-velocity constant, substrate concentration at one-half the maximum growth rate (mg/L)

The amount of biogas from the anaerobic reactor was measured using a gas flow meter (Model LFM 300, Alexander Wright, Co.). The methane and carbon dioxide contents of the biogas were analyzed using a gas analyzer (GA 94A, Geotechnical Instruments (UK) Ltd.). The analysis of nitrogen, phosphorus and protein in duckweed samples was conducted following the Korean Food Analysis Method.<sup>16)</sup> Standard methods<sup>17)</sup> were used for the analyses of the raw wastewater and effluent.

## RESULTS AND DISCUSSION

### Anaerobic Digestion

Table 2 shows the results of the anaerobic digestion experiments; specifically, it gives the efficiencies of removal of total solids (TS), volatile solids (VS), total chemical oxygen demand (TCOD), and soluble chemical oxygen demand (SCOD) as average values at HRTs of 20, 30 and 40 days. Solids and COD removal

Table 2. Effluent organic concentration and removal efficiency as a function of HRT.

Parameters	HRT 20 days		HRT 30 days		HRT 40 days	
	Eff. conc. (mg/L)	Rem.(%)	Eff. conc. (mg/L)	Rem.(%)	Eff. conc. (mg/L)	Rem.(%)
TS	28,111	36.7	30,632	46.3	23,142	46.3
VS	19,551	43.3	21,200	52.1	15,164	54.5
TCOD	27,663	46.6	26,076	59.3	17,847	64.7
SCOD	2,982	57.3	1,923	76.8	1,350	79.5

efficiency increased with increasing HRT. Higher organic removal efficiency was observed at longer HRTs.

When the ammonia-nitrogen concentration exceeds 3,000 mg/L, then the ammonium ion itself becomes quite toxic regardless of pH and the process can be expected to fail.<sup>18)</sup> In the present experiments, however, the concentration of NH<sub>4</sub>-N in the reactor during operation remained below approximately 1,500 mg/L, and hence NH<sub>4</sub>-N did not inhibit the normal operation of the system.

### Biogas Production and Mass Balance

Figure 1. shows the biogas production as a function of VS volumetric loading rate at each HRT, and Figure 2. shows the CH<sub>4</sub> content of

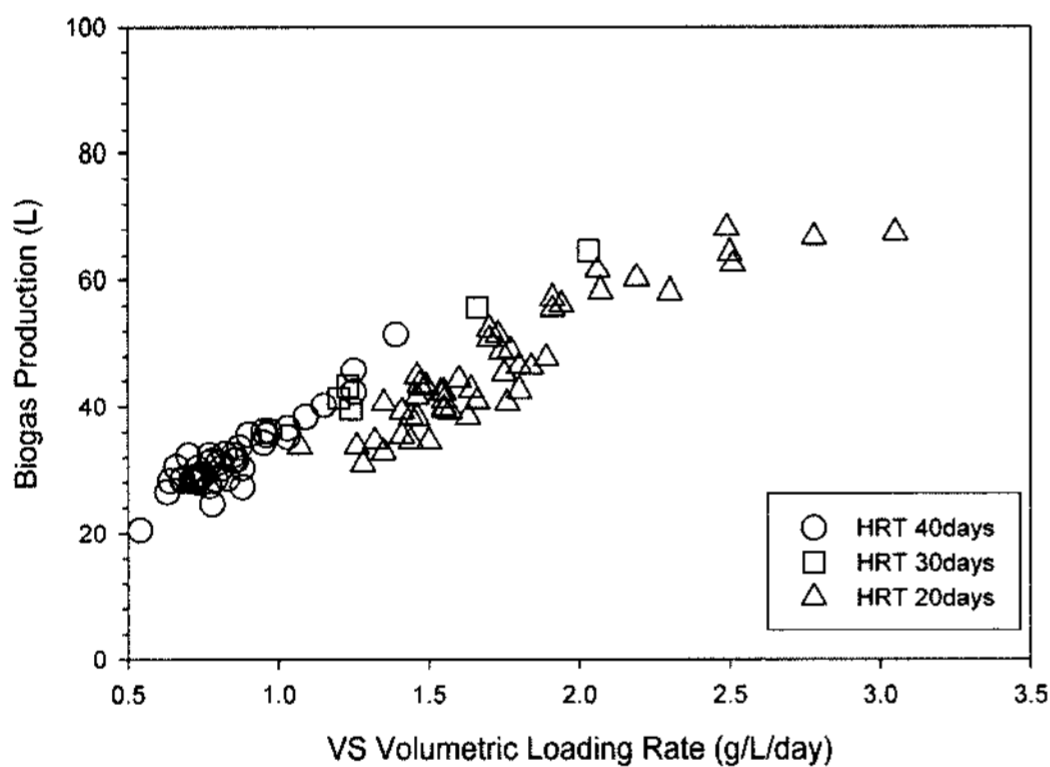


Figure 1. VS volumetric loading rate vs. biogas production.

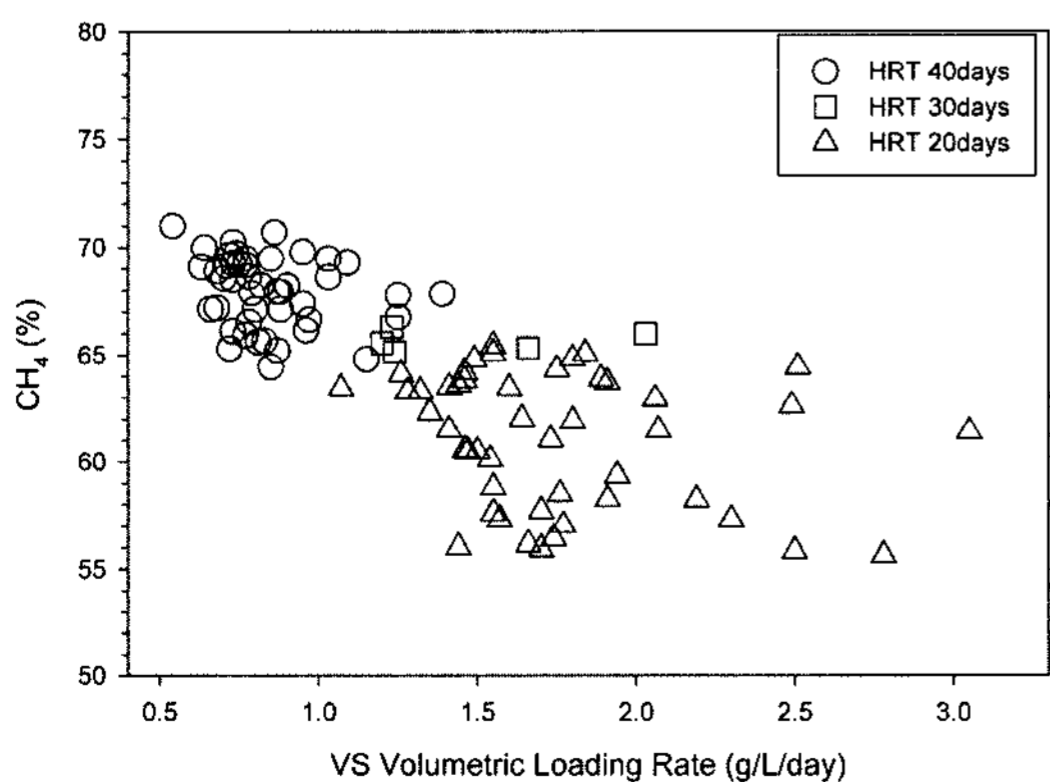


Figure 2. VS volumetric loading rate vs. CH<sub>4</sub> content of biogas.

the biogas as a function of VS volumetric loading rate. The results show the VS volumetric loading rate increases, more biogas is produced but the CH<sub>4</sub> content of the biogas decreases. In addition, at a similar VS volumetric loading rate, the amount of biogas produced and the CH<sub>4</sub> content of this gas increased with increasing HRT.

Figure 3. shows the variation in biogas production rate and CH<sub>4</sub> content with HRT. The biogas production was 46.2 L/day at HRT 20 days, increased to 48.9 L/day at HRT 30 days, but decreased to 32.0 L/day at HRT 40 days. In contrast, the CH<sub>4</sub> content of the biogas increased with increasing HRT.

During the experimental period, in COD mass balance according to variation of HRT, removed COD at HRT 20, 30 and 40 days were 80.6±20.7 g, 84.9±22.3 g and 54.1±10.6 g, respectively. On the basis of these results, the theoretically predicted values of CH<sub>4</sub> production are 28.2±7.3 L at HRT 20 days (STP (0°C, 1atm): 0.35 L CH<sub>4</sub>/g CODrem × 80.6±20.7 g CODrem), 29.7±7.8 L at HRT 30 days and 19.0±3.7 L at HRT 40 days. To correct for the volume occupied by water vapor, the biogas was assumed to be saturated with water vapor as it was collected and measured at a temperature equal to or lower than the reactor temperature. It was also assumed that there was no significant solute reduction at the water vapor pressure. To account for the effects of temperature and water vapor, the average values of CH<sub>4</sub> content were multiplied by the dry biogas factor (at 35°C: 0.8317) calculated by Richards *et al.*<sup>19)</sup> to account for these effects. After this adjustment, the revised values of CH<sub>4</sub> production were 23.5±5.0 L, 26.9±6.0 L and 18.2±3.3 L at HRT 20, 30 and 40 days, respectively. Comparing the measured CH<sub>4</sub> gas production with the amount of CH<sub>4</sub> gas predicted theoretically based on COD removal, the measured values of CH<sub>4</sub> gas production at HRT 20, 30 and 40 days correspond to 84%, 91%, and 97% of the theoretical values, respectively. Thus the amount of CH<sub>4</sub> produced

Table 3. COD mass balance in anaerobic digestion.

Parameters	Input COD Mass(g)	Output COD Mass(g)	Removed COD Mass(g)	Biogas (L)	CH <sub>4</sub> (%)	Theoretical CH <sub>4</sub> pro.(L)	Empirical CH <sub>4</sub> pro.(L)	Empi./Theo.
HRT 20days	171.8 ±32.9	91.3 ±16.2	80.6 ±20.7	46.2 ±10.0	61.0 ±3.0	28.2 ±7.3	23.5 ±5.0	0.84 ±0.06
HRT 30days	142.0 ±30.2	57.1 ±8.3	84.9 ±22.3	48.9 ±10.8	65.7 ±0.5	29.7 ±7.8	26.9 ±6.0	0.91 ±0.04
HRT 40days	83.6 ±14.1	29.5 ±5.2	54.1 ±10.6	32.0 ±5.4	68.0 ±1.7	19.0 ±3.7	18.2 ±3.0	0.97 ±0.05

in the experiments coincides relatively well with the theoretical values, taking into account the microbe concentration in the anaerobic digester, the COD consumed for cell synthesis, sulfate reduction, and the quantities of CH<sub>4</sub> dissolved in the anaerobic digester and in the effluent.

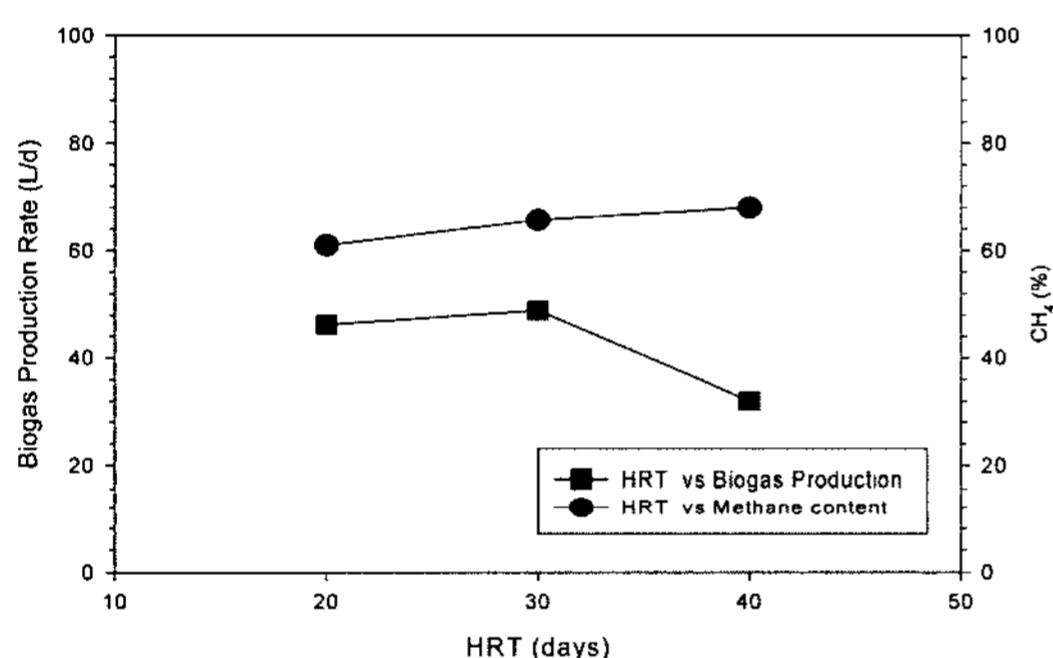


Figure 3. Biogas production rate and CH<sub>4</sub> content of biogas as a function of HRT.

## Aquatic Plant System

### Nutrient Removal

The system was operated over a range of influent organic and nutrient concentrations up to the maximum concentrations in which duckweed could survive. The loading rate was increased by using the anaerobic digestion effluent which is diluted with tap water. The swine wastewater used in this research contained not only high strength organics and nutrients but also had a high fat content that led to formation of a fatty layer on the water surface that caused the aquatic plants to become submerged and to aggregate. Because the fatty layer interfered with the suspend characteristic of the duckweed, duckweed could not

grow under conditions of over 70 mg of NH<sub>4</sub>-N per liter.

The influent loading rate of NH<sub>4</sub>-N in the aquatic plant experiments ranged from 0.06 to 2.57 g/m<sup>2</sup>/day, and the total removal efficiencies for the systems with these loading rates were found to be 34.1% to 97.9% (Figure 4). The amount of NH<sub>4</sub>-N remaining after treatment increased with an increase in the concentration and loading rate of the influent. It was found that for all systems with influent NH<sub>4</sub>-N loading rates of 1.0 g/m<sup>2</sup>/day or less, the concentration of NH<sub>4</sub>-N in the effluent was below 10 mg/L and the removal efficiency was over 60%.

Figure 5. shows the effect of varying the concentration and loading rate of PO<sub>4</sub>-P in the influent on the removal efficiency and effluent PO<sub>4</sub>-P concentration. The concentration of PO<sub>4</sub>-P in the influent varied from 0.28 to 11.02 mg/L, and the loading rate varied from 0.01 to 0.42 g/m<sup>2</sup>/day. The removal efficiency decreased with increasing concentration and loading of influent. For systems with PO<sub>4</sub>-P loadings below about 0.15 g/m<sup>2</sup>/day, the effluent concentration was below 2.0 mg/L and removal efficiency was over 55%.

These results indicate that under appropriate operational conditions, the effluent quality is within the limits set by Korean discharge criteria. Thus, the method described here could potentially be used in full-scale swine wastewater treatment plants to reduce the total nitrogen and phosphorus in the wastewater to within legal limits for effluent discharged into sensitive receiving waters.

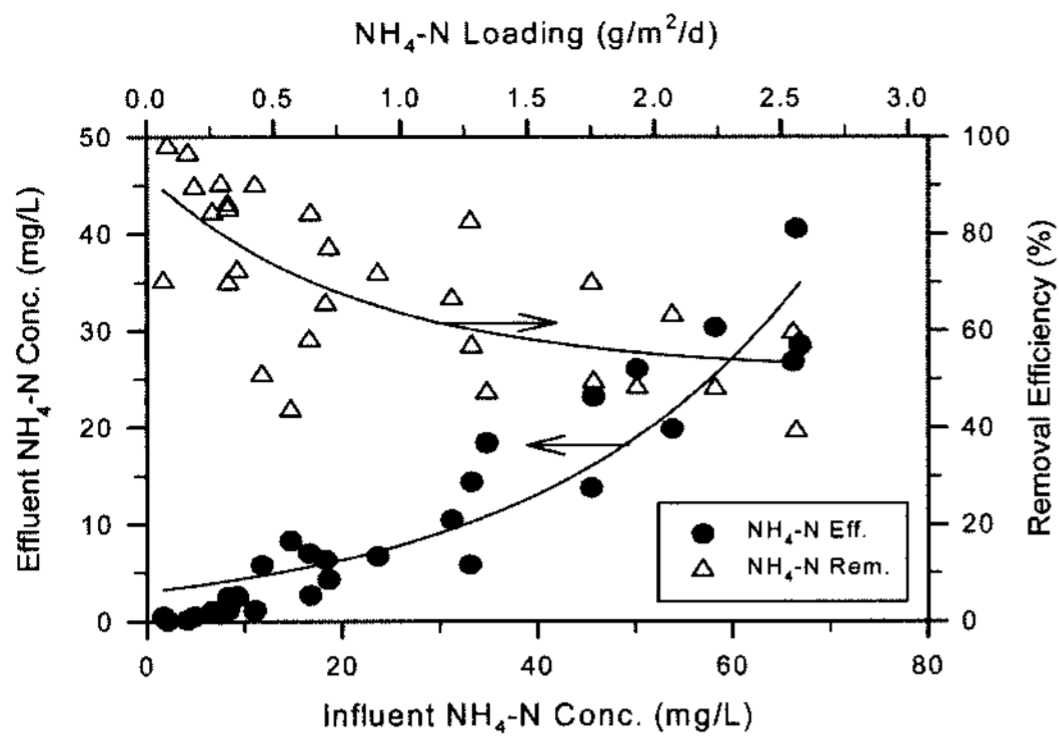


Figure 4.  $\text{NH}_4\text{-N}$  removal efficiency with influent  $\text{NH}_4\text{-N}$  concentration.

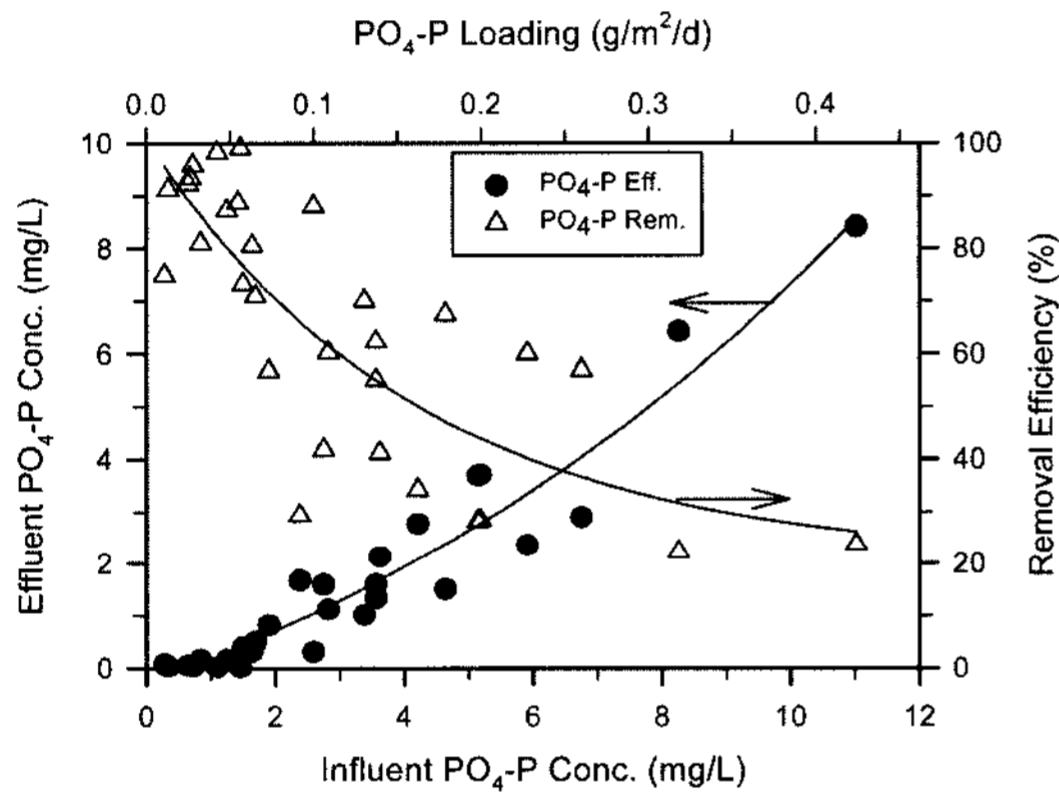


Figure 5.  $\text{PO}_4\text{-P}$  removal with influent ortho-P concentration.

### Growth Characteristics

Figures 6. and 7 show the specific growth rate of duckweed as a function of the concentrations of nitrogen and phosphorus. The duckweed growth rate was good with increasing concentration of nitrogen, and a maximum specific growth rate was  $0.34 \text{ day}^{-1}$ . This maximum growth rate of duckweed was about 3.3 times faster than the growth rate of water hyacinth reported by Jun<sup>20)</sup>.

As for nitrogen, the duckweed growth rate also increased with increasing concentration of phosphorus, reaching a maximum specific growth rate of around  $0.34 \text{ day}^{-1}$ . This maximum growth rate is about 3.5 times faster than the maximum growth rate of water hyacinth growing in a phosphorus solution reported by Jun,<sup>20)</sup> and is about 1.4 times faster than the maximum growth rate of *Salvinia natans* as a function of phosphorus concentration.<sup>21)</sup> The half saturation constants were

$1.565 \text{ mg/L}$  of nitrogen ( $K_N$ ) and  $0.172 \text{ mg/L}$  of phosphorus ( $K_P$ ).

The specific growth rate of duckweed observed in the present work was high ( $0.132 \sim 0.363 \text{ day}^{-1}$ ), and the doubling time ( $1.9 \sim 5.3 \text{ days}$ ) was similar to that found by Reddy and Debusk.<sup>22)</sup>

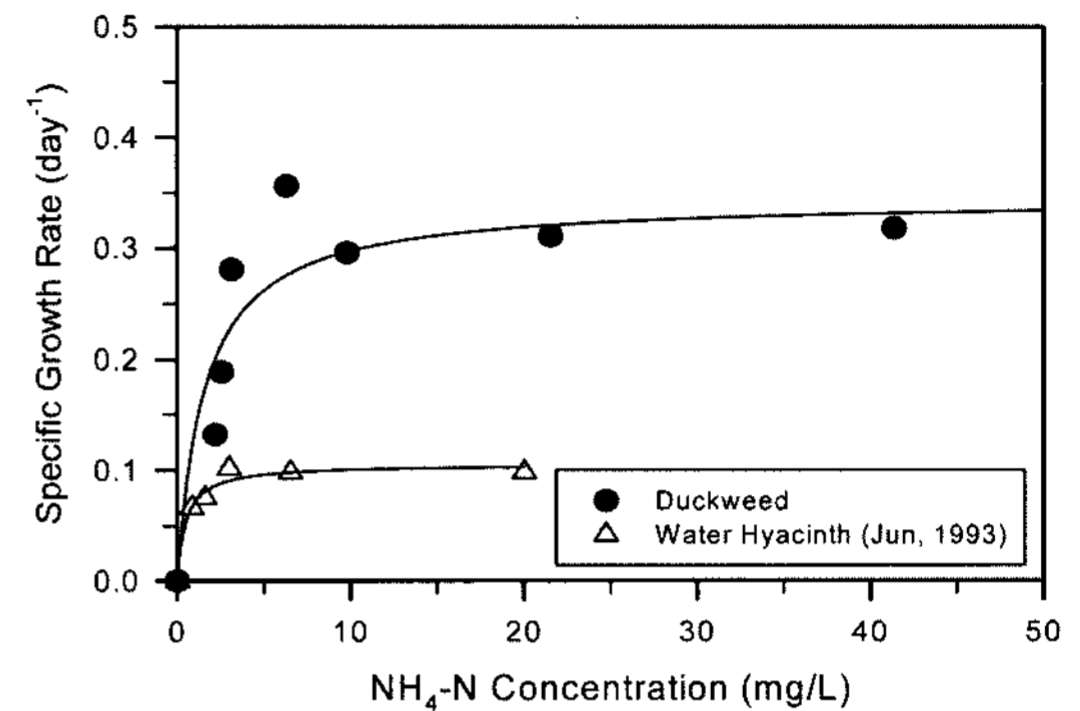


Figure 6. Specific growth rates with influent ammonium nitrogen concentration.

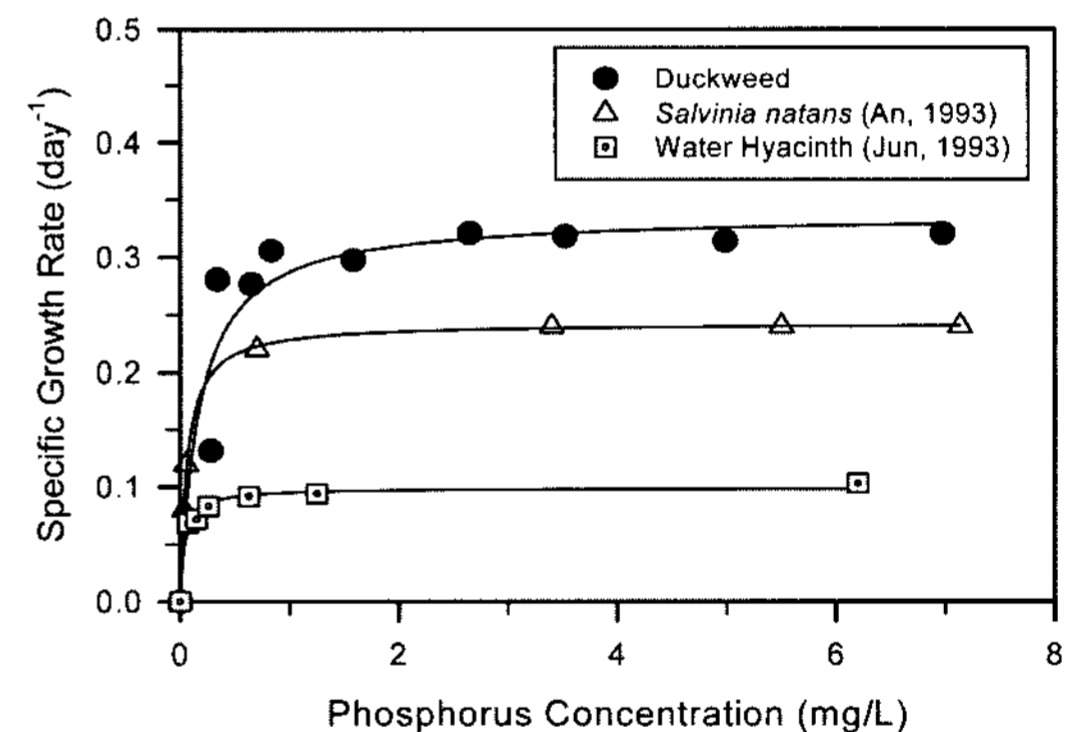


Figure 7. Specific growth rates with influent phosphorus concentration.

Table 4 shows the growth rate and maximum specific growth rate for duckweed grown in phosphorus and nitrogen, along with the corresponding data for water hyacinth<sup>20)</sup> and *Salvinia natans*.<sup>21)</sup>

Figure 8. shows the crude protein content of duckweed tissues as a function of the influent  $\text{NH}_4\text{-N}$  concentration and the phosphorus content of duckweed as a function of the influent phosphorus concentration. As the  $\text{NH}_4\text{-N}$  concentration increased, the crude protein content rose from 15.6% to 41.6 %, with the protein content remaining at about 40% in duckweed samples grown in influent containing more than 30 mg/L

Table 4. Specific growth rate of duckweed with various nutrient concentration.

Items	Nitrogen		Phosphorus		
	Duckweed	Water Hyacinth <sup>20)</sup>	Duckweed	Water Hyacinth <sup>20)</sup>	Salvinia natans <sup>21)</sup>
$\mu_{max}$ (day <sup>-1</sup> )	0.344±0.030	0.105±0.005	0.338±0.021	0.097±0.003	0.243
KS (mg/L)	1.565±0.687	0.410±0.130	0.172±0.066	0.032±0.007	0.071
SGR (day <sup>-1</sup> )	0.132~0.363	-	0.132~0.363	-	-
Doubling time (days)	1.9~5.3	6.3~6.9	1.9~5.3	6.9~7.4	2.9

NH<sub>4</sub>-N.

Similarly to the crude protein content data, the phosphorus content of the duckweed increased with increasing concentration of phosphorus in the influent. The phosphorus content of the duckweed ranged from 0.81% to 1.62% and remained at around 1.5% for influent phosphorus concentrations above 3.5 mg/L.

The results of the present experiments on the use of aquatic plants to treat anaerobic digester effluent from a swine wastewater show that the crude protein content and nutrient content of the plants increased with increasing nutrient concentration in the culture water. These results are in accordance with the work of Edwards,<sup>23)</sup> who found that the nutrient content in duckweed increases to levels as high as the nutrient concentration in the water in which the duckweed grows.

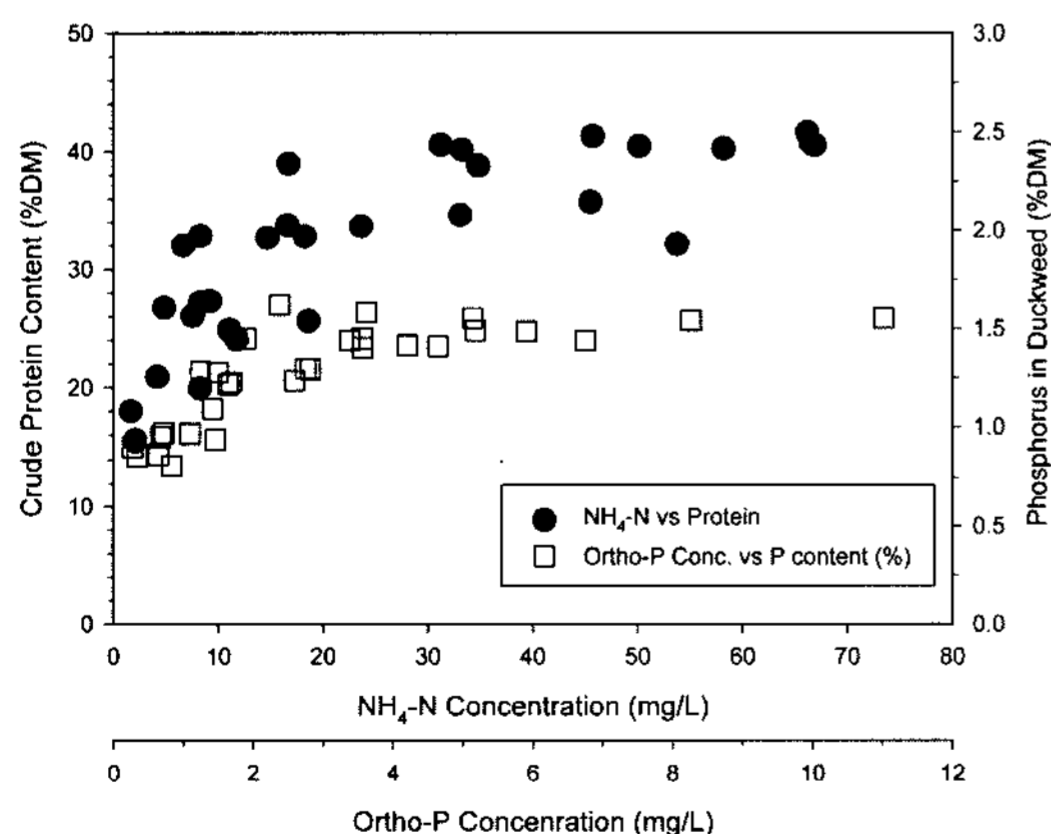


Figure 8. Crude protein and phosphorus content with influent ammonium nitrogen concentration and influent ortho-P concentration.

## CONCLUSIONS

The following conclusions can be drawn with

regard to the treatment of high strength swine wastewater using anaerobic digestion and aquatic plants:

- 1) Anaerobic digestion gave VS removal efficiencies of 43.3%, 52.1% and 54.5% for HRTs of 20, 30 and 40 days, respectively. Organics removal efficiency decreased with increasing influent VS volumetric loading rate and increased with increasing HRT.
- 2) As the VS volumetric loading rate increased, biogas production increased but the CH<sub>4</sub> content of the biogas decreased. At a given volumetric loading rate, biogas production and biogas CH<sub>4</sub> content both increased with increasing HRT.
- 3) Treatment of the anaerobic digestion effluent with NH<sub>4</sub>-N loadings of up to 1.0 g/m<sup>2</sup>/day with duckweed reduced the effluent nitrogen concentration to below about 10.0 mg/L and showed a nitrogen removal efficiency of over 60%. In the case of phosphorus, duckweed treatment of anaerobic digester effluent with PO<sub>4</sub>-P loadings up to 0.15 g/m<sup>2</sup>/day reduced the concentration of effluent to below 2.0 mg/L with a removal efficiency of over 55%.
- 4) The specific growth rate of duckweed varied over the range of 0.132 day<sup>-1</sup> to 0.363 day<sup>-1</sup> according as variations of the influent nutrient concentration. Experiments independently varying the concentrations of nitrogen and phosphorus gave maximum specific growth rates in the presence of these nutrients of 0.344 day<sup>-1</sup> and 0.388 day<sup>-1</sup> respectively.
- 5) The duckweed grew faster in effluent with high nutrient concentrations than in effluent low in nutrients. The crude protein content and phosphorus content of duckweed increased with increasing nutrient concentration, showing

values of about 40% DM and 1.5% DM for duckweed grown in high concentration substrates.

- 6) The treatment of high-concentration swine wastewater by anaerobic digestion combined with an aquatic plant system offers good performance in terms of the removal of organics and nutrients. Moreover, duckweed tissue contains at least twice as much protein, nitrogen, and phosphorus as water hyacinth tissue, making partially dried duckweed a more attractive food source for animals and poultry. The results indicate that under appropriate operational conditions, the proposed method gives effluent qualities within the limits set by Korean discharge criteria.

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