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Management and utilization of biodigesters in integrated farming systems

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Abstract

Two studies were conducted at the University of Tropical Agriculture from 10th May to November 6th 2002. The first was: "The effect of retention time on gas production and fertilizer value of biodigester effluent" and the second: "Effluent from biodigesters with different retention times for primary production and feed of Tilapia (*Oreochromis niloticus*)".

In the first study, two experiments were carried out to determine gas production and fertilizer value of the effluent in plug-flow, tubular, plastic biodigesters with hydraulic retention times of 10, 20 or 30 days. There were three biodigesters each of 510 litres liquid volume in each experiment which consisted of three consecutive periods (retention times) of 40 days arranged in a 3*3 Latin Square. In experiment 1, the quantity of fresh pig manure was 5.1 kg/day, mixed with 46, 20 or 12 litres of water to give retention times of 10, 20 or 30 days, respectively. In experiment 2, the proportions of pig manure and water were maintained constant to give a total solids content of 60 g/litre in the influent, which was added at rates of 51, 25.5 and 17 kg daily for retention times of 10, 20 or 30 days, respectively. Gas production was measured daily by water displacement in inverted lightweight containers (tubular polyethylene supported by bamboo strips) suspended in 200 litre drums filled with water. Influent and effluent were analyzed at weekly intervals for DM, OM, pH and total nitrogen and ammonia-nitrogen. Gas production was measured daily but only the data for the last 10 days of each period were used in the statistical analysis.

With a fixed daily input of fresh manure, neither the rate of gas production (1.04, 1.20 and 1.12 volumes of biogas per unit liquid volume of the biodigester) nor the efficiency (493, 606 and 567 litres of biogas/kg of manure organic matter added to the biodigester), were influenced by retention time (10, 20 or 30 days, respectively). However, when the solids concentration of the influent was fixed at 60 g/kg, rates of gas production were reduced by increasing retention times (1.62, 1.19 and 0.81 volumes biogas/unit liquid volume of biodigester for 10, 20 and 30 days retention); efficiency was better for 20 and 30 days retention (550 and 547 litres biogas/kg OM) than for 10 days (376 litres/kg OM). The proportion of ammonia-N in total-N increased from a range of 0.023 to 0.029 in the fresh manure to a range of 0.40 to 0.60 in the effluent and did not appear to be affected by retention time or loading rate.

It is concluded that when fresh pig manure is the substrate in polyethylene plug-flow biodigesters the optimum retention time is between 10 and 20 days with a solids concentration in the influent of 60 g/litre. The retention time apparently has no effect on the degree of conversion of organic N to ammonia-N.

In the second study, the effluent from the experiment with constant solid concentration (60g/kg) were used for fertilizing tilapia ponds. A randomized complete design was used to study growth rate of Tilapia (*Oreochromis niloticus*) as influenced by pond fertilization (0.133g N/m^2/day) with effluents from biodigesters having hydraulic retention time of 10 and 30 days. There were three replications (ponds of 6 m^2 in area) of each treatment which was applied over a period of 120 days.

Growth rate and net fish yield were higher with effluent from 30 day retention time (0.43g/day and 1363 kg /ha) than with effluent from 10 day retention time (0.27g/day and 899 kg/ ha). Mean values for BOD_5 were higher for the 10 day retention time.

It is concluded that the improved fish productivity with effluent from biodigesters with 30 day, compared with 10 day, retention times was probably due to a combination of lower BOD in the pond water, and a higher proportion of ammonia-N in the effluent.

Keywords: Biodigester, effluent, gas production, pig manure, fertilizer value, polyethylene, retention time, primary production, tilapia, Oreochrmis niloticus,

Introduction

The integrated farming system is part of the strategy to ensure sustainable use of the natural resources for the benefit of present and future generations (Preston 1995). While immediate attention has been given in the industrialized countries to ensure adequate material supplies to fuel their energy-intensive food systems (Ignacy Sachs and Dana Silk 1990), long-term concerns were raised about the difficulty of the rural and urban poor in third world countries with the realization that the high cost of energy and fertilizers would be a major limitation to their development (Preston and Leng 1989).

In practically all third world countries the problems of getting enough food to eat began to be overshadowed by the problems of acquiring the energy needed to cook it. Apart from the financial costs, there is a severe strain on time budgets, notably those of women and children, who spend increasingly long hours collecting fuel wood (Cecelski 1987). These problems are exacerbated by the seasonal imbalance in biomass supply and the vicious cycle of greater quantities of dung being used as fuel rather than as fertilizer for maintaining crop production. Hence, this strategy is not sustainable; the more appropriate technical option in this case is to convert the manure to biogas through anaerobic digestion. The biogas can be used to satisfy household fuel demand instead of the manure that before was use as fuel for cooking. The effluent from the biodigester is a replacement for chemical fertilizer for use on land crops, or in ponds for production of water plants and fish (Preston 2000; Barbara 2000). The concept of the integrated farming system is shown in Figure 1.

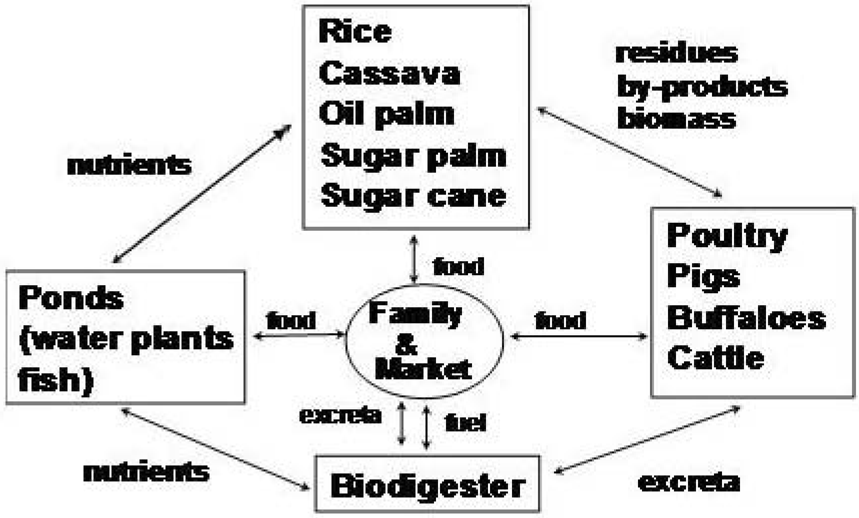

Figure1: The flow diagram of an integrated farming system (Source: Preston 2000)

Fuel wood and energy

Long (1992) reported that a family of 5 persons in Guangxi , China uses the equivalent of 2100 kg/year of firewood as fuel. There are no rural electricity services in Cambodia and the country does not have a transmission network. Wood energy is the most important energy source, with almost 84% of total energy for cooking derived from this source in 1994, and 96% of households using wood as the major fuel for cooking (FAO-RWEDP 1998-2000). It has been estimated that less than 18% of Cambodia's energy use is commercial (MIME/ADB 1996). The remaining 82% is from wood with petroleum products accounting for less than 2% of household energy use.

Waste of manure

The manure in remote rural areas of Philippines is often a source of environmental pollution (air pollution and water pollution) (Moog et al 1997), because few animals are raised and most of the manure is used as raw fertilizer in the field or for cooking, when dry, or is put in a hole for make compost. The latter is a rural Cambodian practical experience. On the other hand, large scale intensive animal enterprises, with pigs or poultry, on limited land areas, are major sources of environmental pollution, in the atmosphere and water. This is because the manure has no immediate use on these farms (usually no crop land available) and is allowed to flow into rivers, lakes or ponds. This accumulation of organic matter will be fermented or digested and partly released as methane and carbon dioxide to the atmosphere or ionized to minerals which leach into the ground (Henrik 2000). This problem of inappropriate use of livestock wastes can be solved by applying the anaerobic digestion process (Henrik and Pat 2000).

Biodigesters

The use of tubular plastic biodigesters for anaerobic digestion to convert organic matter to biogas and effluent (Botero and Preston 1995) is a very simple and practical system that is flexible and uses low-cost materials (Preston and Rodríguez 2002; Mette 1998; Bui Xuan An et al 1997) when compare to other types of biodigester (Mikkle et al 1996; Timothy and Gohl 1996).

The result of the anaerobic digestion is the production of a biogas mixture of methane and carbon dioxide. The composition of biogas varies depending on the raw materials, the organic load applied, the time and temperature. On average, it is about equivalent to the following: methane (CH_4) 55-65%, carbon dioxide (CO_2) 35-45%, nitrogen (N_2) 0-3%, hydrogen (H_2) 0-1% and hydrogen sulphide (H_2S) 0-1%. Biogas is about 20 percent lighter than air and has an ignition temperature in the range of 650 to 750 ºC. It is an odourless and colourless biogas that burns with a blue flame similar to that of Liquefied Petroleum Gas (LPG) (Sathianathan 1975). The effluent from the digester has from 60 to 80% less BOD (Biological Oxygen Demand) compared with the input material (Arthur 2000). It has been shown to be a high quality fertilizer (Preston and Rodríguez 2002; Le Ha Chau 1998a,b).

The polyethylene tube biodigester is continually being researched and promoted in Vietnam and Cambodia (Nguyen Duong Khang and Le Minh Tuan 2003; Bui Xuan An et al 1997; Preston and Rodríguez 2002). In my research in Cambodia, it was observed that with daily loading of 5 kg manure solids, one cubic meter of digester capacity (liquid volume) would produce about 1.61 m³ biogas daily (San Thy et al 2003). Thus for a family of 6 in the developing world, digester systems of liquid capacity of 4 to 6 m³ can meet the daily biogas requirements. A similar conclusion was reached by Luitweiler (No date).

Factors that influence biogas production

Temperature

There is a close relationship between the biogas fermentation process and the temperature of the reactor. The higher the temperature, the more biogas is produced but when temperature is too high this can cause the metabolic processes to decline as the microorganisms cannot tolerate the conditions and enzymes become degraded (Marchaim 1992).

Bacteria are classified according to their preferred temperature. Spycrophilic bacteria work best between 10 and 20 ºC, mesophilic between 20 and 30 ºC and thermophilic bacteria between 45 and 60 ºC. Anaerobic digestion is very efficient in the thermophilic range, but rural type digesters use mesophilic bacteria, as temperatures higher than 35ºC are very hard to obtain. For mesophilic bacteria the optimum digestion occurs at about 35ºC whereas for the thermophilic range the optimum is 55ºC (Marchaim 1992).

A stable temperature is very important to maintain gas production as the bacteria are very sensitive to changes in temperature. Experiences in China (Anonymous 1992) indicate that a rapid change of more than 5oC will slow down the gas production noticeably. This can be a problem when there are major differences in day and night ambient temperatures. It may be one of the reasons for the low gas production in digesters at high altitudes, where the digester has to work in the lower mesophilic and spycrophilic range. A solution might be to situate the digester further underground in these areas. The lower temperature, provided it is stable, will not harm the bacteria, but the fermentation will take longer and therefore it is necessary to make the retention time as long as possible (up to 100 days) in areas where the temperature goes below 20 ºC. Another solution is to insulate the digester with some form of cover which will let the heat through. This can also be a way to prevent solar radiation harming the plastic, and also makes a good protection for children and animals (Fulford 1988). In my research (San Thy et al 2003), the ambient temperature (27 to 30.3 ºC) was in the range of the mesophilic bacteria.

Concentration of solids

The solids concentration in the influent to the biodigester affects rate of fermentation (Marchaim 1992). In temperate latitudes, as in most of China, the optimum concentration of solids was considered to be 6% in summer but between 10 and 20% in winter and spring. When temperatures are low and materials take longer to decompose, it is better to have a higher solid concentration, although this might cause a problem with impeded flow through the digesters (Anonymous 1992). The concentration of total solids in the input suspension can be varied within the range of 20 to 100g/litre. For plug-flow tubular plastic biodigesters, in practice, it is recommended to limit the total solids concentration to the range of 20 to 30 g/litre (Bui Xuan An and Preston 1999). In Nepal, 6 kg of cow dung per m^3 of digester liquid volume is used (FAO/CMS 1996). In my research, the optimum concentration for pig manure in a plug-flow plastic biodigester was found to be 60 g/litre of solids with a retention time of 10 days (San Thy et al 2003).

Retention time

The amount of gas produced depends on the volume of slurry in the biodigester (the liquid volume), being normally about two thirds of digester volume (Fulford 1988). The digester volume is also related to the retention time measured in days and the loading rate, in terms of manure solids per unit liquid volume (San Thy et al 2003). According to experiences in China (Anonymous 1992), 97% of the total yield of gas from fermenting cattle manure will be produced in a period of 50 days at 35 ^{o}C.

In order to have a retention time of 50 days, the daily input in a 4 m^3 digester should be: volume of slurry: 2 /3x4 = 2.7 m^3 and daily input: 2.7 m^3 /50 days = 54 litres /day; total solids content in cattle manure of 17 % (theoretical value). In order to have a total solids content of 5% in the influent, the amount of fresh manure should be: 0.05*54 liters /0.17 = 15.8 kg of fresh manure and 38.2 litres of water (assuming the density of the influent is 1000 kg/m^3). In 5 or 6 m^3 digesters the amount of manure and water should be respectively: 19 kg of manure to 47.0 litres of water, and 23.5 kg of manure to 56.5 litres of water (Lotte et al 1995).

The higher the loading rate the more gas is produced but the efficiency of gas production is reduced (Boodoo et al 1979). The retention time should therefore be determined as a balance between efficiency and rate of gas production.

Volatile solids (VS) and loading rate

The loading rate is defined as the amount of volatile solids (fermentable solids) per unit of active biodigester volume per day. Typical values for loading rates are between 0.2 and 2 kg VS/m^3/day. The loading rate for a 5 m^3 digester with an input of raw manure of 15.8 kg is equal 0.413 kg VS/m^3/day. This assumes that total solids (TS) are 17% of the fresh weight of the manure and that the volatile solid content (VS) is 77% (Fullford 1988).

Loading rate of field digesters varied from 0.33 to 2.03 kg VS/m^3/day in the study done by Lotte et al (1995). If the loading rate is too high, there will be more substrate than the bacteria can decompose, which will cause a holdup in the methane producing step, as the methanogens multiply more slowly than the acid forming bacteria. The acid will inhibit the methane producing bacteria and thus gas production. Furthermore, if the bacteria are removed with the effluent faster than they are able to replace themselves, it mean that the retention time is too short, the main symptom will be that the digester is becoming sour; the crucial point here is to inoculate with already digested material.

The methane content of the gas can indicate overloading but it is more difficult to measure unless the right equipment is available. If the digester is being overloaded the gas production will rise up initially and then fall after a while when inhibition occurs. The CH_4 content of the gas will fall while the CO_2 content will rise, because CO_2 is not used by the hydrogen consuming bacteria or because the methanogenic bacteria are inhibited. Typical values for methane content are in the range 50 to 60% CH_4 for animal manure and up to 75% CH_4 for feedstock containing fats (Marchaim 1992). The proportion of CH_4 to CO_2 in the gas, depends on the substrate and is also slightly affected by temperature, pH and pressure. Therefore, if these parameters are changed, overloading cannot be predicted based on the CH_4 content alone.

Inocula

Biogas production is not possible without a sufficient quantity of biogas microbes. These are often low in number in fresh material. Taking some of the effluent (10 to 30 % of daily input) and putting it back into the digester is a way of inoculating the fresh manure with the active microbial flora. This inoculation of fresh manure can increase gas production up to 30% and it is very important in a plug-flow digester as there is almost no mixing between old and fresh slurry (Lotte et al 1995).

pH values

The pH gives an indication of chemical factors in the digester. Biogas fermentation requires an environment with neutral pH and when the value is below 6 or above 8 the process will be inhibited or even cease to produce gas because of the toxic effect on the methanogen population (Anonymous 1992). The optimum for biogas production is when the pH value of the input mixture in the digester is between 6 and 7. Increasing the amount of feedstock or a change in fermentation material is likely to acidify the fermentation system because of accumulation of volatile fatty acids (VFA). In this way pH can be used to indicate if the system is being overloaded. In the initial period of fermentation, as large amounts of organic acids are produced by acid-forming bacteria, the pH inside the digester may fall below 5 causing inhibition of the growth of the methanogenic bacteria and hence reduced gas generation (Da Silva 1979). Acetate and fatty acids produced during digestion tend to lower the pH of digester liquor (Marchaim 1991). Hansen et al (1998) stated that acetate-utilizing methanogens are responsible for 70% of the methane produced in biogas reactors.

Some of the CO_2 produced by the bacteria dissolves in the water to form dehydrogenate carbonate (H_2CO_3) which is in equilibrium with bicarbonate ions (HCO_3^-). The HCO_3^- causes the solution to become mildly alkaline and the amount of the HCO_3^- depends on the concentration of CO_2 and amount of acid in the slurry. A better measure than pH for the stability of the digester is therefore alkalinity which indicates the buffering capability of the fermentation system. If the pH drops it indicates that the buffering system has already failed and too much acid is being produced usually because the methanogenic bacteria have stopped working. Methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6.5. Later, as the digestion process continues, the concentration of NH4 increases due to digestion of nitrogen which can increase the pH value to above 8. When the methane production level is stabilized, the pH range remains buffered between 7.2 and 8.2 (FAO/CMS 1996).

Feed materials and nutrients

Anaerobic digestion processes are able to utilize a large number of organic materials as feedstock, including animal manure, human waste, crop residues, food processing and other wastes or a mixture of one or more of these (Marchaim 1992). Animal manure has a good nutrient balance, is easily made into a slurry and is relatively biodegradable in the range of from 28 to 70% (Lotte et al 1995), the variation being partly due to the diet of the animal. Cattle manure is an easy feedstock to use for a biogas plant, as it already contains the right bacteria from the ruminant of the cow (Fulford 1988). Pig and poultry manure however produce more biogas per unit weight and at higher rates because of a lower carbon: nitrogen (C:N) ratio. Human waste is also high in nitrogen and therefore a good feedstock for digestion. Goat and sheep manures are rich in nutrients but they are in a form of pellets that must be broken up mechanically.

Raw plant material is bound up in plant cells with cellulose and lignin which are difficult to digest. Raw vegetables usually need some form of physical or chemical treatment before use. A good idea is to compost vegetable matter for a few days before adding it to the digester. Plants with little lignin such as water hyacinth or duckweed can also give quite high gas yields (Fulford 1988). Materials with different C: N ratios differ widely in the yield of biogas, the ideal C: N ratio being between 20:1 and 30:1 (Marchaim 1992). Materials with a low C: N ratio (25:1 or lower) are the excreta from humans and animals, while materials with a high C: N ratio are residues of agricultural plants. If the C: N ratio is high, the gas production can be improved by adding nitrogen in form of cattle urine, or by fitting a latrine to the plant (Fulford 1988). Gas production and composition is according to the feedstock of material that is fed to the biodigester (Tables 1 and 2).

Microbiology and biochemistry

Digestion by anaerobic bacteria in the mesophilic digestion is an effective method for educing the concentration of pathogenic bacteria found in the excreta of some farm animals (Duarte et al 1992). These bacteria include enteric bacteria, fungal spores, parasite eggs and some viruses. Destruction of microbial pathogens is much more effective at thermophilic temperatures (Bendixen et al 1992).

The process of substrate decomposition and methane production for methane fermentation is according to the general stiochiometric equation shown in Figure 2 (Kenealy and Zeikus 1981).

$$C_nH_aO_b + (n-a/4-b/2)\ H_2O = (n/2-a/8+b/4)\ CO_2 + (n/2+a/8-b/4)\ CH_4$$

The carbon dioxide reduction theory is developed on the basis acetate oxidation should result in the removal of hydrogen and methane with carbon dioxide serving as a terminal electron acceptor. Imhoff (1938) reported that there are four kind of metabolic groups that function in anaerobic digestion:

(1) the hydrolytic and fermenting bacteria that convert a variety of complex organic molecules to end products

(2) the hydrogen producing acetogenic bacteria that can convert the products of the first group (organic acids larger than acetic acid and neutral compounds larger than the methanol) to hydrogen and acetate

(3) the homo-acetogenic bacteria that convert a very wide spectrum of multi- or mono-carbon compounds to acetic acid and

(4) the methanogenic bacteria which convert H2 and CO2, monocarbon compounds and acetate, into methane or can form methane from decarboxylation of acetate.

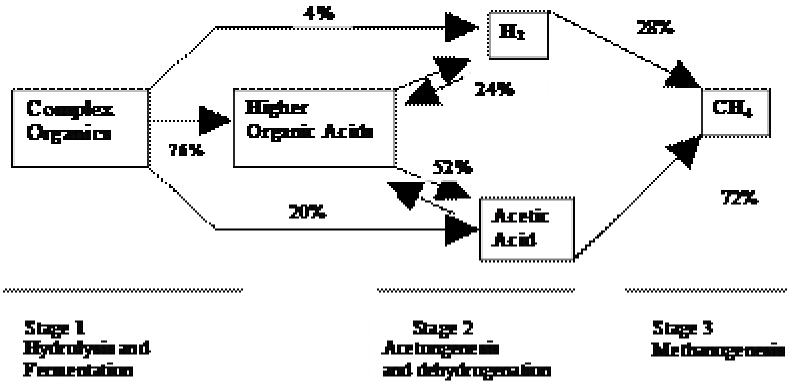

Figure 2: The stages of methane fermentation (Marchaim 1992)

Biogas composition and energy

Table 1: Biogas production and composition from different feedstocks

Feedstock	Total solids (TS), %	Volatile solid (VS), % of TS	Biogas yield, m^3/kg VS	Methane content, vol. %	Retention time, days
Pig slurry	3-8	70-80	0.25-0.50	70-80	20-40
Cattle slurry	5-12	75-85	0.20-0.30	55-75	20-30
Chicken slurry	10-30	70-80	0.35-0.60	60-80	>30
Garden waste	60-70	90	0.20-0.50	-	8-30
Fruit waste	15-20	75	0.25-0.50	-	3-20
Food remains	10	80	0.50-0.60	70-80	10-20

Source: Steffen et al (2000)

Table 2: The composition of biogas produced by anaerobic digestion

Component	Natural gas	Biogas
Volume %		
CH_4	85	55-80
CO_2	0.89	20-45
C_2H_6	2.85	-

C_3H_8	0.37	-
C_4H_{10}	0.14	-
N_2	14.35	-
O_2	<0.5	-
mg/ m^3		
H_2S	<5	0-15000
NH_3	-	0-450

Sources: Shoemaker and Visser 2000; Guidebook on landfill gas extraction and utilization 1997; Manure digestion in the Netherlands 1990

Biodigester effluent

The quantity of effluent coming from a biodigester depends on the charging rate and retention time; while the quality as fertilizer depends on the nature of the feedstock, it's composition, the loading rate and the retention time (Henrik 2000). The fertilizer value of the influent and effluent from digesters charged with manure from pigs and cattle is shown in Table 3.

Table 3: The average content of dry matter, pH, and N compounds in biodigester feedstocks from pigs and cattle and in the effluent

	pH	**DM, %**	**Total-N g/kg**	**Ammonia-N g/kg**	**Total N/ammonia-N**
Pig	7.2	3.8	4.8	3.6	0.7
Cattle	7.1	7	4.3	2.6	0.6
Effluent	7.6	4.9	4.6	3.3	0.7

Source: Henrik (2000)

The use of the effluent in aquaculture

Water quality

Biochemical oxygen demand (BOD)

The BOD value, which is waste specific, is highly correlated to the amount of dry matter in the waste. Decomposition is also temperature dependent and thus low temperatures will result in slower breakdown and hence higher BOD values. As a rough guide, rates of decomposition reduce by 50% for every 5oC temperature drop. The use of BOD values in effluents used in aquaculture (Table 4) facilitates estimating safe levels of organic matter that can be added to ponds, ensuring the minimum needs of dissolved oxygen for the fish. The fresh manure has a higher BOD than composted manure, fermented manure and effluent from biodigesters (Ding Jieyi and Han Yujin 1984). For instance, the BOD for biodigester effluent is about 60 to 70% lower than in fresh manures (Bio Cycle 1999; Pich Sophin and Preston 2001). The BOD varies according to the fertilization (Table 4).

Table 4: The 24 hour biochemical oxygen demand (BOD) for various inputs into pond culture of fish

Material	**BOD (g O_2/ kg/24 hr) at 30^{o}C**
Dry human wastes	35-50
Chicken manure	20-40
Duck manure	20
Terrestrial fodder	13
Pig manure	12

Field day manure	10
Submerged aquatic weeds	8.6
Liquid cowshed manure	7
Floating aquatic weeds	6.3
Emergent aquatic weeds	5.4
Liquid calf manures	5
Human sewage	2.5-3

Sources: Almazan and Boyd 1978; Edwards 1982; Schroeder 1978

Oxygen

There are two main sources of oxygen in water; diffusion from the atmosphere and through the photosynthesis of aquatic plants, mostly phytoplankton. The atmosphere contains nearly 21% oxygen gas, but solubility in water is low, so the greater amount of oxygen in the water comes from the process of photosynthesis. There are three main factors that influence level of dissolved oxygen in the pond; temperature, photosynthesis and respiration. This oxygen is used by plankton, fish and benthic organisms for respiration and for the decomposition of organic material. Oxygen solubility decreases with increasing temperature (Table 5) and increasing salinity. The magnitude of daily changes in oxygen concentration is influenced by phytoplankton density. Oxygen is lowest at sunrise, before photosynthesis becomes active, increases during the daylight hours to peak in late afternoon or early evening, and declines at night. Oxygen consumption rates by fish vary with water temperature, dissolved oxygen concentration, fish size, level of activity, time after feeding, and other factors. Metabolic rates vary by species and are limited by low oxygen conditions; small fish consume more oxygen per unit size than large fish of the same species.

Swingle (1969) developed a dissolved oxygen (DO) scale for warm-water fish:

- DO: < 0.3 mg/litre : Fish die after short-term exposure
- DO: 0.3 mg to 1 mg/litre : Lethal for long- term exposure
- DO: 1mg to 5 mg/litre: Fish survive, but growth is slow for long-term exposure.
- DO ³ 5mg/litre : minimum for warm water fish (fast growth)

Fish do not grow well when the DO concentration is below 25% of saturation for long periods (Romaire 1985). Fish perform better when DO concentrations are near saturation. Some authors recommend that the DO concentration in aquaculture systems be kept at about 90% of saturation, as a minimum at all times, for optimum performance.

Table 5: The effect of temperature on oxygen saturation of water

Temperature (^{o}C)	**Oxygen saturation (mg/litre)**
10	10.9
15	9.76
20	8.84
25	8.11
30	7.53
35	7.04

Source: STOAS 1993

pH

pH is important in aquaculture as a measure of the acidity of the water or soil. Fish can not survive in waters below pH 4 and above pH 11 for long periods. The optimum pH for fish is between 6.5 and 9. Fish will grow poorly and reproduction will be affected at consistently higher or lower pH levels (Table 6).

The pH of most natural waters ranges between 5 and 10 (Boyd 1990) and it changes according to the influence of many factors such as acid rain, pollution, and CO2 from the atmosphere and fish respiration. The decay of organic matter and oxidation of compounds in bottom sediments also alter pH in water bodies. In ponds, phytoplankton and other organic plants use up CO2 during photosynthesis, so the pH of a water body rises during the day and drops at night. In poorly buffered pond waters the pH can be as low as 5 to 6 in the morning rising to 9 or more in the afternoon. In waters with high alkalinity, pH typically ranges from 7.5 to 8.0 at daylight and from 9 to 10 in the afternoon. According to Randall (1991), in general, fish are intolerant to pH extremes outside of the range of 5 to 9. In my research (San Thy and Preston 2003b), the range of pH in the fish ponds was from 8.63 to 9.01, which is within the desirable range for fish growth and reproduction.

Table 6: The effects of pH on warm-water pond fish

pH	Effect on fish
4	Acid death point
4 to 5	No reproduction
4 to 6.5	Slow growth
6.5 to 9	Desirable ranges for fish reproduction
9 to 10	Slow growth
³ 11	Alkaline death point

Source: Swingle 1969

Nitrogenous compounds

The major source of nitrogen (up to 90%) in an aquaculture system is from fish feeds and is produced through the normal metabolic processes of the fish. Most of the nitrogen in organic matter exists as the amino acids in protein. The chemistry of nitrogen in ponds is very complex because of the many states in which nitrogen can exist: NH_3, NH_4^+, N_2, N_2O, NO, N_2O_3, N_2O_5, NO_2^-, and NO_3^- (Sawyer and McCarty 1978). The form of nitrogen will affect the processes in the system (Table 7).

Table 7: The major forms of nitrogen in aquaculture systems

Form	Notation	Comments
Nitrogen gas	N_2	Inert gas; transfers in and out from atmosphere; no significance.
Organic nitrogen	Org-N	Decays to release ammonia.
Un-ionized ammonia	NH_3	Highly toxic to aquatic animals; predominates at high pH levels.
Ionized ammonia	NH_4^+	Nontoxic to aquatic animals except at very high concentration; predominates at low pH levels.
Total ammonia	$NH_3 + NH_4^+$	Sum of unionized and ionized ammonia; typically measured in the test for ammonia; converted to nitrite by nitrifying bacteria.
Nitrite	NO_2^-	Highly toxic to aquatic animals; converted to nitrate by nitrifying bacteria.
Nitrate	NO_3^-	Nontoxic to aquatic animals except at very high concentrations; readily available to aquatic plants.

Source: Boyd 1990

The nitrogen cycle

Ammonia is produced through the biological conversion of organic nitrogen through a process called ammonification (Figure 3). Ammonia is also produced as the major end product of protein catabolism and is excreted by fish and invertebrates (Campbell 1973). It is excreted primarily as non-ionized ammonia (NH3) through the gills. Ammonia is also produced through the decomposition of urea, fish faeces, and uneaten feed.

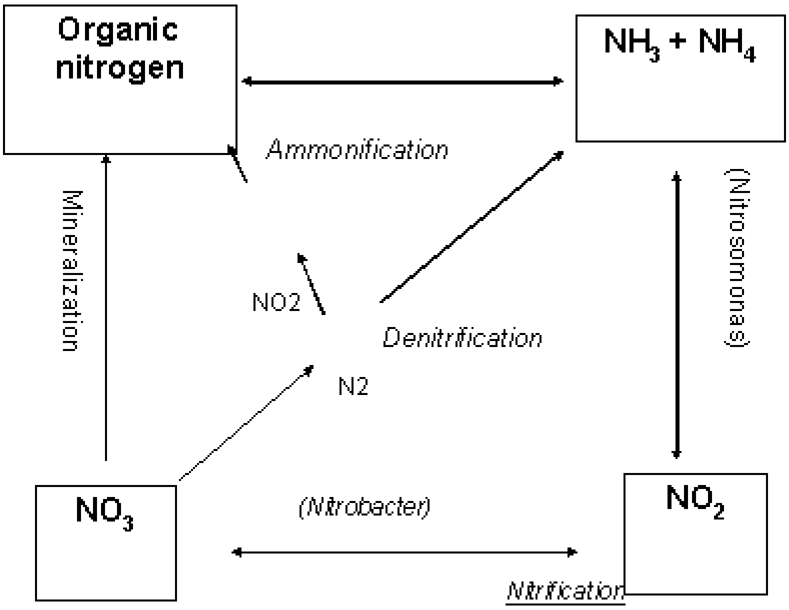

Figure 3: The nitrogen cycle

Ammonia

Ammonia can be in two states: ionized ammonia also called the ammonium ion (NH_4^+) and non-ionized ammonia (NH_3). The two sources of ammonia ($NH_4^+ + NH_3$) are called total ammonia or simply ammonia. Total ammonia nitrogen (TAN) = NH_4^+ + NH_3-N. The toxicity of TAN is dependent on what fraction of the total is in non-ionized form since this is by far the more toxic of the two. In most environments NH_4^+-N predominates; although the fraction present in this form is dependent on pH, temperature and salinity. Water pH has the strongest influence on the direction in which the equilibrium equation will shift.

$$\mathbf{NH_3 + H_2O = NH_4OH = NH_4^+ + OH^-}$$

When the pH value is lower, the reaction will shift to the right and as pH is raised the reaction will shift to the left. Toxic concentrations of NH_3-N for short-term exposure vary between 0.6 and 2 mg/litre for many pond fish, and some effects can be seen at 0.1 to 0.3 mg/litre (Boyd 1979). Normally warm-water fish are more tolerant to ammonia than cold-water fish. To be safe, ammonia concentrations below 0.05 mg/litre as NH_3-N and 1.0 mg/litre as TAN are recommended for long-term exposure.

Nitrite

The nitrite and nitrate concentrations show distinct seasonal patterns in fish ponds because nitrite (NO_2-N) is the ionized form of nitrous acid (HNO_2), and it can be as lethal as NH_3-N. Nitrite levels in fish ponds typically range from 0.5 to 5 mg/litre, probably due to the reduction of nitrate in anaerobic mud or water (Boyd 1982). They both are usually minimal in the summer months and increase in autumn, winter and spring. The toxicity of NO_2-N is due principally to its effects on oxygen transport and tissue damage.

Nitrate

Nitrate buildup occurs most in pond systems when water temperature is lower. The nitrosomonas bacteria, which convert ammonia to nitrite, function at cool temperatures (16-20^{o} C), but nitrobacter, which convert nitrite to nitrate, do not function well at temperatures this low, hence nitrite will accumulate. Neither species functions well at temperatures below 16 ^{o} C.

Nitrates are the least toxic of inorganic nitrogen compounds. The effects on aquatic animals are similar to nitrite having to do with osmoregulation and oxygen transport, but the concentrations at which fish are affected are much higher. The safe values of NO_3-N for many fish and invertebrates lie between 1000 to 3000 mg/litre (Colt and Tchobanoplous 1976).

Wastes and aquaculture production

Organic waste utilization in aquaculture can either be extensive, with wastes occurring naturally or being added, with little or no further production management (Bardach et al 1972).There are specific sites, often with inadvertent fertilization by run-off, where fish yields are very high. An example is a duck farm where the wastes can produce up to 1.3 tonnes fish/ha in 100 days. Where the wind also concentrates the plankton, yields may be as high as 3 tonnes or more of fish/ha/100 days (reference needed??). A comparable level of fish productivity prevails in the more typical fish ponds with more material inputs.

In China, when animal wastes are applied there is often additional extraneous feeding (Ding Jieyi and Han Yujin 1984). In these situations, the 100-day fish yield reaches 3 to 4 tonnes/ha. Other examples are in Table 9. Sandbank (1990) made an experiment on wastewater-fed fish culture in Israel with tilapia and showed that the net fish yield was 5076 kg/ha in 240 days and 2184 kg/ha in 120 days, whereas Moscoso and Nava (1990) reported that in a tilapia culture pond fertilized with effluent, the fish production was 2290 kg/ha in 154 days. The fish yield in my study (San Thy and Preston 2003b) was 1828 kg/ha in 120days.

Sewage oxidation ponds are also good bases for aquaculture (Han Yuqin and Ding Jieyi 1983). Tilapia and silver carp were stocked in an oxidation pond and compared to an oxidation pond not containing fish (Table 8) (Schroeder 1975). Bacteria levels were lower in the pond containing fish, perhaps because the disinfection potential of waters with high pH and higher oxygen content is greater. The high pH probably results in a higher rate of loss of ammonia to the atmosphere, considered to be beneficial from the waste-treatment point of view, and also from the viewpoint of fish health management (ammonia is toxic to fish) (Lu and Kevern 1975). The high oxygenation of fast-flowing water, of balanced sewage ponds, or of balanced fish ponds receiving organic wastes, does not permit the survival of most such pathogens (Table 8) (Allen and Hepher 1976).

Table 8: General properties of primary treated sewage effluent

Parameter	Concentration
BOD_5 (mg/litre)	12.0-360
pH	6.5-7.3
DO (mg/litre)	0.7-13.5
CO_2 (mg/litre)	51.4- 128
Organic carbon (mg/litre)	48.0-98.2
NO_3-N (mg/litre)	Trace- 0.82
NH_4-N (mg/litre)	Trace- 65.2

Source: Schroeder 1975; Jhingran and Ghosh 1990

Table 9: Representative net fish yields (NFY) of sex-reversed male Nile tilapia raised for five months (initial stocking weights about 10 g/fish) in culture ponds with low inorganic turbidity and alkalinities above 75 mg/litre CaCO3, and where at least 90% of the fertilizer N and P came from chemical fertilizers. Fertilization input was at fixed rates of approximately 30 kg N/ha/d and 10 kg P/ha/wk.

Stocking rate, fish/m^2	**Mean final weight,** g/ fish	**NFY**, kg/ha/d	**NFY**, kg/ha/yr	**Reference**
1.6	244	31.7	11,558	Knud-Hansen and Pautong (1993) (200 m2 ponds, Thailand)
2.0	170	22.6	8,249	Knud-Hansen and Batterson (1994) (400 m2 ponds, Thailand)
2.0	157	23.3	8,504	Knud-Hansen and Batterson (1994) (400 m2 ponds, Thailand)
0.8	350	14.9	5,429	Knud-Hansen and Lin (1996) (200 m2 ponds, Thailand)

The value of organic wastes

In a polyculture fish farm in Israel, as one instance, the yields were reasonably high (4150 kg/ha/yr). It should be noted that in polyculture systems, nutrients are reused as they pass through the digestive tracts of the various component species (Rawitscher and Mayer 1977). The use of manure and domestic sewage, however, represents a saving for the fish farmer only when these materials are available. Their use prevails in many parts of tropical Asia, in India, in communes in China, and in the kibbutzim of Israel, where land-animal husbandry and aquaculture are practiced conjointly (STOAS 1996; Tapiador et al 1977; Allen and Hepher 1976; Yashouv 1966). Examples of this are provided by a pig-cum-fish polyculture experiment (Buck et al 1978). Overall productivity of biomass was increased by 67 % with no additional feeding or fertilizer by providing pig wastes to a polyculture pond. Feed conversion efficiency increased from 3.8:1 in the pig-only system to 2.2:1 in the pig-cum-fish system. Conversion of feed nitrogen was 58 per cent in the pig-only system, versus 70 per cent in the pig-cum-fish system.

Anaerobic digestion has been reported to increase manure ammonia content (manure being a preferred kind of agricultural nitrogen fertilizer), from 26 % in raw unprocessed manure, to 50% following digestion (Sanghi and Day 1977). However, the extent to which anaerobically-treated sludge and supernatant can be substituted for untreated manure in a fish pond and still maintain high yields of fish has not been demonstrated. This is a very important consideration, because organic substances added to a pond can be consumed directly by heterotrophic organisms and by-pass the photosynthetic production level. Thus, production of fish using organic manures can greatly exceed levels predicted for a pond based entirely on an ecosystem starting with light-limited plants that utilize inorganic nutrients.

Direct feeding

Feeding types among fishes range from predatory gulpers to sifters of organic materials in mud, to zooplankton feeders, and to herbivores that eat algae or even leafy plants. As already intimated, the rationale of polyculture is the selection of compatible species with different feeding habits. In addition, as fish learn to feed on almost anything, it is relatively easy to develop pelleted foods for fish culture, dietary quality considerations aside. At the same time, such feeding habits permit the use of plant materials, especially cheap or nearly valueless crop residues. Bardach (1978) illustrates this, as does the practice of building very wide pond limitations around the fish ponds in China for cultivating grasses where leafy-plant-feeding grass carp (Ctenophryagodon idella) comprise about 20 per cent of the stock in the pond (Tapiador et al 1977).

All sorts of other wastes, even sludge, are fed to fish tilapia (Kerns and Roelofs 1977; Viola 1977; Bayne et al 1976) with very low conversion efficiencies, but presumably favoring cheap production costs.

Conclusions

- Natural resources are being depleted and this is a signal to promote more efficient use of existing resources. The efficient utilization of livestock manure in integrated farming systems is one way to assist poor rural farmers through improved feed security, reduced dependence on outside inputs and increased income.
- The logical approach is the use of the manure to feed biodigesters in order to have a dual purpose approach to stabilize the environment and improve the health condition, because biodigesters have an important role for reduction of pathogens and conversion of organic N to ammonia N. It is a potential “factory” for improving the integrated farming system, providing low cost energy, and fertilizer to improve crop production in rural households.
- The benefits of the integrated farming approach are the many positive impacts at smallholder farmer level. These include biogas for cooking, reduced deforestation, less labor and time for finding firewood and improved human health through less use of open fires and, especially, the use of effluent from the biodigester as a source of nutrient inputs for agricultural production systems.
- The balance of the evidence indicates beneficial effects on fish production from the use as fertilizer of biodigester effluent rather than fresh manure, but the results are often confounded by associated effects of supplementary feed. There is a need for more information on the effects on fish growth of processing manure through biodigesters, especially the low cost plastic model, which is a relatively recent development in developing countries.

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