WATER AND SEDIMENT QUALITY IN DIFFERENT INTENSIVE SHRIMP CULTURE SYSTEMS IN SOUTHERN THAILAND

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Abstract

The production environment of shrimp farms is constantly changing, necessitating adaptive solutions to new problems. The emergence of highly pathogenic viral disease and deteriorated water supplies has resulted in a tendency to reduce water exchange in Thai intensive shrimp farms. The actual requirement for water exchange has also been questioned as new pond management techniques become available. This study compares the pond water quality from intensive shrimp production systems at different stages of the culture cycle (high water exchange, low water exchange, zero water exchange and lined ponds). Results show that ammonia increases through the production cycle in all systems, however, the zero water exchange system had potentially stressful ammonia concentrations for the last quarter of production (3.00 $mg.l^{-1}$). Other nitrogenous compounds increased through production but were not significantly different and not considered stressfully high. Lined ponds (0.72 - 0.79 $mg.l^{-1}$) had significantly higher total phosphorus concentrations than the other systems during the last month of production (0.21 - 0.40 $mg.l^{-1}$); this was concluded to be due to lower lime applications, pond soil acidity and the absence of pond sediments in lined ponds. There was no significant effect of pond system or stage of culture on suspended solids concentrations (98 - 183 $mg.l^{-1}$), however, the organic content of the solids differed between systems. The effect of system type on Chemical Oxygen Demand (COD) was surprising, since highest values were found in lined pond and mangrove ponds with high water exchange (8.4 - 9.2 $mgO_2.l^{-1}$). Zero water exchange systems which could be expected to have high organic loadings were not significantly different from low water exchange systems (6.0 - 7.7 $mgO_2.l^{-1}$). This suggests that sedimentation and stabilization of the organic matter in shrimp ponds is an important process in determining pond water quality. The effects of pond lining on sediment quality was also investigated. Accumulated sediment in lined ponds has a significantly higher ammonia, water and organic content, however, the overall amount of sediment accumulated is very low. The physical characteristics of sediments from lined and unlined ponds reveals that the sediment from lined ponds can be easily removed by pumping during production. This has significant management implications for low water exchange systems. Total effluent nutrient loadings were significantly lower in the zero water exchange system than the other systems studied. This shows the potential for minimising environmental impact through reduced water exchange. There is a need for further development of management strategies to allow the maintenance of a healthy rearing environment whilst reducing effluent impact.

Introduction

The maintenance of good water quality in shrimp production ponds is essential in providing a low stress rearing environment for Penaeid shrimp (Wyban, Sweeney and Kanna, 1988; Lin, 1989; Chien, 1992; Phillips, Lin and Beveridge, 1993; Funge-Smith and Briggs, 1996). Traditionally the method of water quality management has been through the use of water exchange to flush excess plankton and nutrients out of the pond. Due to increasing farm density, deteriorating influent water quality and the rise in viral disease, there has been increasing resistance amongst farmers to the use of water exchange as a method of pond water quality management (Funge-Smith, 1996).

In Thailand, during the past five years there has been a progression from high rates of water exchange through to zero ('closed system) water exchange strategies (Chanratchakool, Turnbull, Funge-Smith and Limsuwan, 1995; Tiensongrusmee, 1996). A driving force in this tendency is the observation by farmers that water exchange resulted in disease outbreaks in production ponds. Research conducted into viral diseases ('yellowhead' and 'white patch' disease) has suggested that viral disease could be transmitted in water and through crustacean intermediate hosts (Flegel, Boonyaratpalin and Withyachumnamkul, 1996; Fegan, 1996). The conclusion of this has been that minimisation of water exchange will reduce the possibility of disease transmission into shrimp production ponds. Despite the widespread adoption of low water exchange management strategies, major production losses have still occurred in southern Thailand. The attraction of low water exchange systems in other countries of the world lies in the reduction of effluent discharges (Allan and Maguire, 1993; Browdy, Holloway, King, Stokes, Hopkins and Sandifer, 1993; Hopkins, Sandifer and Browdy, 1995). If water exchanges are minimal then only the harvest effluent need be treated. It has also been found that increasing water exchange rates does not always influence pond water quality (Hopkins *et al.*, 1995; Teichert-Coddington, 1996;)

Shrimp pond water quality management through the use of water exchange is a relatively simple method. Farmers in Thailand using this method usually do not attempt to control any parameter other than water colour and transparency (NACA, 1994; Chanratchakool *et. al.* , 1995; Funge-Smith, survey results). In this system, phytoplankton bloom crashes occur occasionally, however, the rapid re-establishment of the phytoplankton bloom prevents long lasting effects of high ammonia and nitrite and low dissolved oxygen (Funge-Smith and Briggs, 1996). Reduction of water exchange requires the closer control of other water quality parameters such as pH and ammonia, effective sediment management, careful control of feeding and reduction of stocking density. In southern Thailand the control of pH fluctuation is considered a priority in an attempt to maintain ammonia predominantly in the less toxic ionised form (Dr. Chalor Limsuwan, pers. comm.). The control of pH is achieved by killing phytoplankton through the use of biocides (benzalkonium chloride, formalin and copper agents). The heavy addition of limes and dolomites in an attempt to influence alkalinity is common (4000 - 16,340 $kg.ha^{-1}.crop^{-1}$, source: survey S. Thailand 1994-1995). Whilst the closed system is heavily promoted as a solution to disease and environmental problems, the ability of small scale, poorly educated farmers to effectively manage water quality and feeding is questionable. This inability increases the potential of risk stressful rearing conditions, fouled water and disease in their ponds, culminating in financial loss.

The use of lined pond shrimp production systems is rare in southern Thailand, due largely to the high initial cost and lack of proven effect on production. The lining of earthen ponds provides a barrier between sediment and water and could potentially improve water quality. The use of liners does prevent erosion of the pond bottom and hence the accumulation of large amounts of sediment in the centre of the pond (Briggs and Funge-Smith 1994). The accumulated sediment is a source of many compounds that are toxic or stressful to the shrimp (Avnimelech, 1996). Lining ponds can minimise sediment accumulation and allow easier removal during production and after harvest. Whilst lining ponds might have potential beneficial effects on water quality, it is uncertain whether these would be sufficient to override the effect of other pond management activities.

The type of soil that the pond is constructed on may also have an effect on water quality due to different erosion characteristics, organic content, redox potential and pH. Again, it is uncertain whether the soil type of a pond is significant relative to the effect of management activities.

This study compares the effect of month of production and system type on pond water quality in five different intensive shrimp production systems - open clay soil, open mangrove soil, semi-closed, closed and lined pond systems. The intention is to evaluate the relative benefits and problems of these different production systems with respect to the pond rearing environment, possible stress effects and potential impacts on the external environment.

Materials and methods

Data from the different pond types and systems in southern Thailand were collected during the period 1992 - 1995. Water exchange strategies from the different systems are presented in Table 1.

Table 1. Percentage water exchange in different shrimp production systems in southern Thailand.

	Percentage Water Exchange ($\%.month^{-1}$)				
Month of production	Open system Clay soil	Open system Mangrove soil	Open system Lined ponds	Semi-closed System	Closed system
1	12	10	10	6	1
2	86	104	104	54	5
3	128	125	125	97	7
4	168	125	125	107	7

The open system ponds monitored (10 ponds) were studied during 1992-1993 in Songkhla province, for a total of 3 production cycles. These ponds were constructed on ex-rice paddy neutral clay soil and abstracted water from the sea. Stocking densities varied between 60 - 100 $pl.m^{-2}$ (further details are given in Briggs and Funge-Smith, 1994).

Water quality data from semi-closed and closed type systems was collected during surveying of farms in four southern Thai provinces (Songkhla, Nakorn Sri Thammarat, Satun, Krabi) during 1994-1995. Water management data and days of production allowed grouping of farms into the relevant water exchange and month of production category. A total of 120 ponds were sampled. Average stocking densities for ponds in these provinces ranged between 76 - 93 $pl.m^{-2}$

Sediment and water quality data were collected from lined (bitumen impregnated geotextile) and mangrove soil shrimp production ponds at the Tinsulanonda Songkhla Fisheries College, Songkhla. Two ponds of each type were monitored weekly over two production cycles during 1994-1995. Stocking densities in these ponds was 65 $pl.m^{-2}$.

Pond management strategies and farmers opinions were recorded through informal conversation and structured interviews at all the sites monitored, to provide additional information for interpretation of the data collected.

Sediment and water quality analysis was performed at the Tinsulanonda Songkhla Fisheries College using the methods described in Briggs and Funge-Smith (1994). The water quality parameters measured were: Total ammonia-N (TAN), Nitrite-N (NO_2-N), Nitrate-N (NO_3-N), Dissolved Reactive Phosphorus (DRP), Total Phosphorus (TP), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Percent organic content of TSS (% Org TSS), Chlorophyll a (Chl *a*).

Accumulated sediment collected from the centre of the mangrove soil and lined ponds was also analysed for: percentage water content, percent organic matter content (ashing 500°C, 18 hours), leachable total ammonia-N, nitrite-N and DRP.

Leachable nutrients were analysed by thoroughly suspending a weighed sample of wet sediment (approximately 10g) in 250 ml of distilled water in a sealed sample bottle. The sediment was settled overnight (18 hrs) at 4°C in the dark. The supernatant was decanted and filtered prior to analysis. Corrections were made to allow for sediment water content and all results are presented as $mg.kg^{-1}$ dry wt. of accumulated sediment. Care was taken to perform the collection and suspension as rapidly as possible to prevent aerobic action on the sediment and modification or volatilisation of the components to be analysed.

The same analytical techniques were employed on all water and sediment samples throughout the study, with samples analysed concurrently wherever possible.

All data was analysed using analysis of variance (significance level $p<0.05$). Results are presented in the form of bar graphs and tables as means including 95% confidence intervals. Comparisons of sediment characteristics were only performed on samples from the lined ponds and the mangrove soil ponds. These ponds were managed by the same farmer in a similar manner.

Results

Water quality parameters

Insert Table 1

Oxygen

Dissolved oxygen concentrations were not affected by month of production but were significantly different between system types. Since chlorophyll a concentrations were similar in all systems this low oxygen concentration was probably due to the low number of aerators on the lined and mangrove soil ponds.

pH

There was a significant difference in pH between the system types until the fourth month of production. There was a significant affect of month of production on pH in all the system types. The pH in the semi-closed system was significantly lower than that in the closed system for the first three months of production. There was no significant difference in pH between the lined and the mangrove soil ponds. The pH levels in the lined and mangrove soil ponds were significantly lower than the other systems. The pH in the open clay system was the highest and most variable of all the systems.

(Fig. 1) Total Ammonia -N (TAN)

There was a significant effect of month of production on TAN concentration. In all systems there was a trend towards increasing TAN concentrations through the production cycle. There was a significant difference between system types after the first month of production. The highest TAN concentrations were found in the closed system ponds, particularly in the third month of production (3.00 $mg.l^{-1}$). The lined ponds and open system clay ponds had the lowest TAN concentrations during the second half of production (0.75 - 1.23 $mg.l^{-1}$). The water exchange in the semi-closed system during the last month of production were sufficient to give TAN concentrations similar to the open systems (1.43 $mg.l^{-1}$). Apart from the first month the mangrove soil ponds had TAN concentrations higher than the other open and semi-closed systems throughout production.

(Fig. 2) Nitrite-N (NO_2-N)

There was a significant difference in NO_2-N concentrations between the systems during production. NO_2-N concentrations were low in all systems during the first month of production (0.01 - 0.1 $mg.l^{-1}$) and increased through the production cycle. NO_2-N concentrations were not significantly different between the open clay soil ponds and the open lined ponds until the fourth month of production. There was also no significant difference between the closed and semi-closed systems throughout production. High concentrations were found in the closed system ponds during the third month of production (0.44 $mg.l^{-1}$) reflecting the high TAN during this period. In the fourth month of production NO_2-N concentrations were highest in the lined pond system (0.41 $mg.l^{-1}$), although this was not accompanied by high TAN. The lowest NO_2-N concentrations during the fourth month of production were in the open clay and mangrove soil ponds (0.05 - 0.11 $mg.l^{-1}$).

(Fig. 3) Nitrate-N (NO_3-N)

There was a significant effect of type of system on NO_3-N concentrations after the first month of production. NO_3-N followed the same trend as NO_2-N, although concentrations were higher in the first two months of production. There was a significant difference between closed and semi-closed systems. The open lined system and open mangrove system were not significantly different throughout production. The open clay system had the lowest NO_3-N concentrations throughout production.

(Fig. 4) Total phosphorus (TP)
TP concentrations were not significantly different between systems during the first month (0.13 - 0.30 $mg.l^{-1}$) and rose through out production in all systems except the open clay system. The lined pond and mangrove systems had significantly higher TP concentration by the fourth month (0.72 -0.79 $mg.l^{-1}$). There was no significant difference between the open clay, semi-closed and closed systems throughout production (0.31 - 0.40 $mg.l^{-1}$).

(Fig. 5) Dissolved Reactive Phosphorus (DRP)
No data was obtained for the lined and mangrove soil ponds for the first 3 months of production. There was no significant difference in DRP concentrations between open clay, closed and semi-closed systems throughout production (0.01 - 0.06 $mg.l^{-1}$). During the fourth month of production DRP concentration was significantly higher in the open lined pond system than the other systems (0.06 $mg.l^{-1}$).

(Fig. 6) Chlorophyll a
There was a significant effect of month of production in all the systems. There was however no significant difference between the systems. Chlorophyll *a* concentrations increased in all systems for the first three months of production (17-45 increasing to 94-158 $\mu g.l^{-1}$). The open clay and mangrove soil systems had very high concentrations in the last month of production (175 $\mu g.l^{-1}$) but concentrations decreased in the lined, closed and semi-closed systems. The decrease in chlorophyll *a* concentrations in the fourth month of production in the lined, closed and semi-closed systems is interesting since this is the time when nutrients in the water (N and P) are maximal.

(Fig. 7) Chemical Oxygen Demand (COD)
COD was not analysed for the open clay system. There was a significant effect of month of production on COD in all systems. Chemical oxygen demand increased in all treatments through the production cycle (4.2 - 5.6 increased to 6.5 - 9.2 $mg.O_2.l^{-1}$), although values in the third and fourth months were similar within the different systems. Highest values of COD were found in the lined and mangrove soil ponds (8.4 - 9.2 $mg.O_2.l^{-1}$). The semi-closed and closed pond systems were not significantly different from each other, neither were the lined and mangrove systems. However the lined and mangrove systems were significantly higher than the closed and semi-closed systems in the third and fourth month of production.

(Fig. 8) Total Suspended Solids (TSS)
There was no significant effect of time or system type on TSS through out production although TSS were slightly lower in the first month of production (72 - 116 $mg.l^{-1}$). After increasing in the second month of production the all systems remained at a similar concentration for the rest of the cycle (98 - 183 $mg.l^{-1}$).

(Fig. 9) Percentage organic content of TSS
Although there was no difference between the TSS concentrations the organic content of the TSS was significantly affected by month of production and type of system. The organic content of the suspended solids decreased significantly through the production cycle in the lined and mangrove soil ponds. In the other systems the organic content was similar throughout production (27 - 36 %). The organic contents of the TSS in the lined and closed system ponds were significantly higher (34 %) than the open clay, mangrove and semi-closed systems (27 - 30 %) during the last month of production.

Sediments from lined and mangrove soil ponds (Table 3.)

There was significantly more leachable TAN in the accumulated sediment from the geotextile lined ponds. However there was no difference in the NO_2-N concentrations between the two types of pond. NO_2-N concentrations were considerably less than TAN concentrations and might have been formed due to the act of sediment removal and exposure to aerobic conditions. Leachable DRP was significantly greater in the geotextile lined ponds than the earth ponds, although variation was high. The water content of the sediment in the lined ponds was significantly greater than the earth ponds. This confirmed the observation that the sediment in the lined ponds was fluid whereas the sediment in the earth ponds had a gel like consistency. The organic content of the sediment from the lined pond was significantly greater than that from the earthen ponds

Table 3. Accumulated sediment analysis from lined and earthen ponds (means ± s.d.)

Parameter	Geotextile liner	Mangrove soil
TAN ($mg.kg^{-1}$)	67.5 ± 27.7	50.8 ± 38.4
NO_2-N ($mg.kg^{-1}$)	0.51 ± 0.44	1.08 ± 1.04
DRP ($mg.kg^{-1}$)	6.8 ± 5.9	2.6 ± 2.5
Water content (%)	85.1 ± 12.7	48.7 ± 19.3
Organic content (%)	35.9 ± 9.1	13.3 ± 5.0

Effluent loadings

Table 4. Nutrient loadings as a result of routine water exchange activities.

	Total effluent loadings as a result of water exchange ($kg.ha.^{-1}.crop^{-1}$) (values calculated for a pond depth of 1.5m, volume 15,000m^3)				
Nutrient	Open system Lined pond	Open system Clay soil	Open system mangrove soil	Semi-closed system	Closed system
TAN	50.5	50.6	95.7	53.9	6.7
NO_2-N	8.8	1.6	3.8	7.2	0.8
NO_3-N	9.8	4.0	5.7	7.8	0.6
TP	34.4	19.0	25.9	13.1	1.2
DRP	1.13	1.49	0.38	0.82	0.12
Chl *a*	0.56	0.71	0.71	0.43	0.03
COD	456.4	n.d.	432.8	244.1	21.1
TSS	6,490	9,312	6,388	5,834	478
Organic SS	1,899	1,723	1,577	1,275	98

The results in Table 4. show that there is no significant difference between any of the systems except the closed pond system, which has significantly lower loadings for all the parameters measured. The lack of water exchange in the closed system results in significantly reduced quantities of discharged nutrients. The lined pond system behaved similarly to the open and semi-closed ponds except in the case of total phosphorus concentration. This was significantly higher in the lined ponds. These loadings do not include the harvest discharges and thus represent potential impact through production until the time of harvest. Approximate harvest loadings can be calculated by multiplying the fourth month value of the water quality parameter concerned by 15 (except chlorophyll which must be multiplied by 0.015) for a value in $kg.ha^{-1}$.

Discussion

Shrimp pond water quality is influenced by both environmental and management factors. Water exchange is a management tool that is intended to reduce of organic, nutrient and solids loadings in a shrimp pond. If water exchange is not being practiced or is significantly reduced it could be expected that the concentration of solids, nutrients and organic matter would increase in the pond system. This is probably the case, however, what is unknown is the extent to which this build up will influence water quality. There are other management and environmental characteristics that might influence water quality; these are the nature and condition of the pond bottom, aeration level, lime applications, feeding rate and stocking density .

The lower oxygen concentrations in the lined and mangrove ponds is probably due to the lower numbers of aerators on these ponds relative to the other systems studied. Chlorophyll *a* concentrations were not significantly different between the systems and increased throughout production. This increase in chlorophyll *a* was not reflected in dissolved oxygen concentrations, which were not significantly affected by month of production. This is unexpected since the phytoplankton bloom is considered to provide the majority of oxygen to a shrimp production pond during daylight hours(Fast and Lannan, 1992). It is possible that another factor was limiting the productivity of the phytoplankton such as free carbon dioxide availability, lack of stirring to continually expose the phytoplankton to daylight.

The pH in the shrimp production ponds is affected by the phytoplankton bloom activity, water alkalinity, pond soil pH and lime applications. The lower pH values in the lined and mangrove ponds are probably due to lack of lime application in this system, since water management and phytoplankton concentrations were similar to the open and semi-closed systems. The mangrove soil and lined ponds were constructed on acid sulphate type soil yet there was no difference between the two systems with respect to water pH. The pH at the sediment water interface was not measured therefore the effect of the liner preventing leaching of acidity is unknown. This data does not show the extremes of pH that may be encountered in these systems as a result of high phytoplankton productivity. The average pH in all the systems is higher than the ideal value for seawater 7.8-8.2, and thus the concentration of the toxic unionised ammonia fraction is increased.

The increase in TAN concentrations through the production cycle is expected, since ammonia is the breakdown product of protein catabolism. Feed applications to the pond increase during production and wastes from the shrimp and leachates from the sediments contribute to the ammonia loading of the pondwater. Ammonia removal is via flushing with clean water or incorporation into phytoplankton or bacterial biomass. Breakdown of ammonia into atmospheric nitrogen is also a potentially significant process (Briggs and Funge-Smith, 1994; Hopkins *et al.*, 1994). The TAN concentrations in the closed system were exceedingly high in the third and fourth months of production (2.63 - 3.00 $mg.l^{-1}$) and well in excess of recommended maximum levels (0.6 $mg.l^{-1}$, Funge-Smith and Briggs, 1994). It is perhaps unsurprising that poor growth, disease and emergency harvesting is typical in this system with such high ammonia concentrations. The reason for avoiding water exchange is to reduce the opportunity for the entry of viral pathogens, yet the water quality conditions within the ponds are certain to predispose animals to opportunist type diseases and stress related production difficulties (slow growth, poor FCR).

The semi-closed system had high TAN concentrations but they were not dissimilar from all the other open type systems. This suggests that although water exchange has the potential to lower TAN concentrations there is a point beyond which its effectiveness is questionable (Hopkins *et al.* 1995). This is reasonable if it is assumed that bacterial and phytoplankton removal of ammonia is a significant process. Excess flushing will tend to lower the concentrations of these organisms and hence reduce their effectiveness (Hopkins *et al.* 1995).

Pond lining did not cause significant reductions in TAN over the open clay and semi-closed systems, but it was significantly less than the mangrove soil ponds which were managed similarly. This indicates that pond lining can reduce the impact of highly organic soils on water quality. The characteristics of the accumulated sediment in the lined ponds showed it had a much more concentrated organic nature (ammonia, organic content) and its flocculated (high water content, dis-aggregated) nature would render its higher nutrient content easily leached.

NO_2-N and NO_3-N concentrations increased throughout production, although they never reached the same concentration as ammonia. Since NO_2-N and nitrate-N are eventual conversion products of TAN the increase and decrease of NO_2-N and nitrate-N tends to follow TAN. This was the case in all systems except the lined pond system which had very high NO_2-N concentrations in the last month of production, yet TAN remained low. The conversion of TAN to nitrite is an aerobic process, but also requires nutrients (carbon source) for the conversion. It is possible that the lined pond, by separating pond soil from the water was limiting bacterial activity in some way. The very low leachable NO_2-N from the accumulated sediments experiment suggests that in the anaerobic conditions of the accumulated sediment there is little nitrite production. The conversion of nitrite to nitrate must therefore occur in the aerobic surface film of the sediments, or in aerobic bacterial flocs in the water column (Fry, 1987; Kirschman and Ducklow, 1987). Bacterial conversion of nitrate to nitrogen gas requires anaerobic conditions, and this very probably occurs in the accumulated sediment. The closed pond system had the highest NO_2-N concentrations overall during production, but in all systems average NO_2-N concentrations did not exceed the critical concentration of 1.0 $mg.l^{-1}$.

Feed application and fertilizers are the principle routes of entry for phosphorus to the ponds (Briggs and Funge-Smith, 1994). The increasing feed application results in increasing phosphorus loading to the pond. Total phosphorus is a measure of the total phosphorus in the water and does not discriminate between free and bound forms. Bound forms can be found as part of the phytoplankton biomass, or adsorbed to solids in the water column. Limes have a strong binding activity to phosphorus and thus loss to the sediments is the major sink for phosphorus in earth ponds (Briggs and Funge-Smith, 1994). In the lined pond system the lack of sediment and low liming rates employed resulted significantly more total phosphorus in the water. The leaching experiments on the accumulated sediment from lined and earth ponds (Table 3) also reveals the higher proportion of phosphorus that is available in lined pond sediments. Thus discharges from lined ponds would have a greater phosphorus impact than earthen ponds. Total phosphorus was also high in the mangrove ponds during the last month of production. This might be a function of the more acidic condition of the pond bottom in this system allowing greater availability.

DRP concentrations were variable throughout production. DRP is the fraction of phosphorus in the water that is considered most bio-available thus rapid uptake of this fraction is likely. It is probable that this fraction is also the most susceptible to sequestration by liming activities, thus DRP seldom reaches high concentrations. The phytoplankton bloom is another sink for available phosphorus.

Although the different systems studied n this work had different characteristics, the overall behaviour of the phytoplankton bloom was similar. Chlorophyll *a* concentration increased through production until the third month. the lack of difference between the systems is partly due to the wide variation in chlorophyll *a* concentrations. It is possible that other factors such as nutrients and stirring are playing a role in phytoplankton dynamics and, in the presence of excess nutrients, these are having the predominant effect.

The overall organic loading of the water (COD) also increased through the production cycle. The lined and mangrove ponds were significantly higher than the open clay, closed and semi-closed systems. This was unexpected since the closed system is probably the system that has the greatest nutrient input (higher stocking density and feeding) and yet the water organic content remains lower than the mangrove and lined ponds. This suggests that sedimentation of organic matter and its incorporation into the accumulated sediment is the most important sink for nutrients. Pond nutrient budgets have shown this (Briggs and Funge-Smith, 1994; Hopkins *et al.*, 1994), however this has not been shown for pondwater quality. If this is the case, then management of the accumulated sediment could be more important than management of the pond water. The removal of sediments through the production cycle is rarely practiced due to farmers' concerns about water quality problems and the consolidated nature of the sediment (source: survey southern Thailand).

The suspended solids concentrations in the different pond systems reveals little difference between production systems and also stage of culture. This suggests that the flushing of ponds does not significantly reduce the suspended solids loadings, or, that the sedimentation of suspended solids is rapid and the solids that remain in the water are non sedimentable (Rubel and Hager, 1979). This latter case seems more likely since sediment accumulation between the lined and unlined systems was dramatically different yet suspended solids concentrations were the same. The lined pond solids accumulation probably did not exceed a few hundred kilos dry weight, yet the earth pond had substantially more. The accumulated sediment originates from the pond bottom and pond walls as a result of erosion and it would seem that this eroded material does not spend long in suspension.

The organic content of the suspended solids revealed significant differences between the system types. The lined pond system had significantly more organic matter in it suspended solids fraction than the mangrove earthen ponds. The lined pond would not provide colloidal material as a result of erosion, and the leaching of nutrients might stimulate greater biological production within the water column. there was no difference between the semi-closed and closed systems until the fourth month of production, when organic content increased in the closed system. This is probably attributable to the lack of water exchange.

The use of water exchange as a method of shrimp pond water quality management is becoming increasingly unattractive to Thai shrimp farmers. The potential entry of poor quality water or disease into a farm via influent water is a risk farmers are increasingly reluctant to take. A potential benefit of reducing water exchange is that impacts via effluent from the system are reduced (Hopkins *et al*, 1994), however, Table 4 reveals that unless the closed system method of water management is employed, there is little or no difference between the other systems. The closed system gives significant reductions in the loadings of all the nutrients studied and thus is a potential method of reducing shrimp farm impact on receiving waters. It is important to note that these are effluent loadings and the inlet loadings must be subtracted to obtain true impact loadings. Generally, the influent water to a shrimp farm has low concentrations of nutrient and solids, thus the effluent loadings are still a good indicator of likely impact.

The reduction of effluent impact is becoming increasingly important in shrimp culture systems due to the high densities of farms that occur in some countries and the strict discharge legislation in others. The problem that faces Thai shrimp farmers is that in systems where water exchange is so minimal, it is not possible to provide a healthy rearing environment.

The very poor water quality that is found in closed shrimp production systems (particularly high ammonia concentration) is undoubtedly predisposing the shrimp to stress related disease. Bacterial and *zoothamnion* diseases were found to be a widespread problem in southern Thai farms (source: survey Southern Thailand) and it is impossible to estimate the production losses from slow growth, stress and opportunist pathogens versus those caused by viral disease. There is now evidence that the viral disease "white patch" is transmittable via postlarvae and thus the role of an environmental component in the expression of this disease seems likely (Fegan, 1996; Flegel *et al.*, 1996). If this is so, then the effectiveness of a truly 'closed' system against viral disease is questionable. Apart from the requirement for clean healthy postlarvae, the best water management option available to farmers would appear to be that of limited water exchange from a treated reservoir. Limited water exchange does enable relatively good water quality conditions to be maintained in the production ponds, whilst reducing the potential of disease introduction to the farm via influent water.

The potential for zero water exchange systems is greater if the nutrients generated within the system could be removed. In this paper and other work it has been indicated that the major sink of these nutrients is the accumulated sediment. Continuous removal of this is highly desirable however there are limitations to this. Various methods of sediment removal have been proposed although principally for the removal of solid accumulated sediment (Hopkins *et al..*, 1994). The sediment must not be excessively disturbed during removal otherwise massive quantities of organic matter and ammonia can be released. The potential for this is shown in the results for the sediment composition and leaching experiments above. The use of drainage pipes is ineffective due to the solid consistency of the accumulated sediment the sediment is only removed in the immediate vicinity of the pipe. This is not a problem with the sediment from lined ponds due to its liquid nature and can be easily drained or pumped. Appropriate pond design incorporating a collection well would facilitate periodic or continuous removal. The low volume and high organic content of dried sediment (Table 4) collected from lined ponds renders it easy to dispose of and improves its potential as a fertilizer.

Minimization of water exchange appears to be a viable method of reducing impacts within and outside shrimp farms, provided the pond environment does not become degraded. The current problem facing the industry in Thailand appears to be one of inadequate management of pondwater quality. Improvements to this system can be made in the form of accumulated sediment removal, limited water exchange from a treated reservoir, efficient feed management and, if possible, reduction in stocking density. Lined ponds are increasingly showing great potential in many countries with respect to minmization of solids impacts and improvement of water quality in ponds built on highly organic or porous soils. It is also apparent that irrespective of whether a pond is lined or not the water quality in the pond is dependent on management activities.

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References

Allan, G.L., Maguire, G.B. and Hopkins, S.J., 1990. Acute and chronic toxicity of ammonia to juvenile *Metapenaeus macleayi* and *Penaeus monodon* and the influence of low dissolved-oxygen levels. Aquaculture, 91: 265-280.

Avnimelech, Y., 1996. Shrimp ponds bottom soils:Process and management. In: Proceedings of the 1996 Annual Meeting of the World Aquaculture Society, Bangkok, Thailand, p.24.

Boyd, C.E., Munsiri, P. and Hajek, B.F.,1994. Composition of sediment from intensive shrimp ponds in Thailand. World Aquaculture. 25(3),53-55.

Briggs, M.R.P. and Funge-Smith, S.J., 1994. A nutrient budget of some intensive marine shrimp ponds in Thailand. Aquaculture and Fisheries Management. 25, 789-811.

Browdy, C.L., Holloway, J.D., King,C.O., Stokes, J.S., Hopkins,J.S. and Sandifer, P.A.,1993. IHHN virus and intensive culture of *Penaeus vannamei*: : Effects of stocking density and water exchange rates. Journal of Crustacean Biology. 13(1),87-94.

Chanratchakool, P., Turnbull, J.F., Funge-Smith, S. and Limsuwan, C., 1995. Health management in shrimp ponds - Second edition. Aquatic Animal Health Research Institute, Department of Fisheries, Bangkok, Thailand, 111 pp.

Chien, Y.H., 1992. Water quality requirements and management for marine shrimp culture. In: J. Wyban (Editor), Proceedings of the Special Session on Shrimp Farming. World Aquaculture Society, Baton Rouge, L.A. U.S.A., pp. 144-156.

Fast, A.W. and Lannan, J.E., 1992. Pond dynamic processes. In: Arlo W. Fast and L. James Lester (Editors), Marine Shrimp Culture: Principles and Practices. Elsevier, Amsterdam, pp. 431-456.

Fegan, D.F., 1996. White Spot Disease of Penaeid Shrimp. Aquastar Laboratories Ltd. P.O. Box 5, Songkhla 90000, Thailand. pp7.

Flegel, T.W., Boonyaratpalin, S. and Withyachumnamkul, B.,1996. Current status of research on yellow-head virus and white-spot virus in Thailand. Proceedings of the 1996 Annual Meeting of the World Aquaculture Society, Bangkok, Thailand. 126.

Fry, J.C., 1987. Functional roles of the major groups of bacteria associated with detritus. In: D. J.W. Moriarty and R.S.V. Pullin (Editors), Detritus and Microbial Ecology in Aquaculture, ICLARM conference proceedings 14, 420p. ICLARM,Manila, Philippines.

Funge-Smith, S.J., 1996. Coastal aquaculture - strategies for sustainability. Final report to the ODA, Project R6011. Institute of Aquaculture, University of Stirling, Scotland.

Funge-Smith, S.J. and Briggs, M.R.P., (in prep). Water quality and nutrient discharge of intensive marine shrimp ponds in Thailand and their relationship to pond productivity. submitted to Aquaculture.

Hopkins,S.J., Sandifer, P.A. and Browdy, C.L.,1994. Sludge management in intensive pond culture of shrimp: Effect of management regime on water quality, sludge characteristics, nitrogen extinction and shrimp production. Aquaculture Engineering, **13**, 11-30.

Hopkins,S.J., Sandifer, P.A. and Browdy, C.L.,1995. A review of water management regimes which abate the environmental impacts of shrimp farming. In: (C.L. Browdy and J.S. Hopkins eds) Swimming through troubled waters. Proceedings of the special session on shrimp farming. Aquaculture '95. World Aquaculture Society, Baton Rouge, Louisiana,USA. 157 - 166

Kirchman, D.L. and Ducklow, H.W., 1987. Trophic dynamics of particle bound bacteria in pelagic ecosystems. In: D. J.W. Moriarty and R.S.V. Pullin (Editors), Detritus and Microbial Ecology in Aquaculture, ICLARM conference proceedings 14, 420p. ICLARM,Manila, Philippines.

Lin, C.K., 1989. Prawn culture in Taiwan. What went wrong ? World Aquaculture, 20(2): 19-20.

NACA, 1994. The environmental management of coastal aquaculture. An assessment of shrimp culture in southern Thailand. Final report to the Office of Environmental Policy and Planning. Network of Aquaculture Centres in Asia-Pacific. January 1994.

Phillips, M.J., Kwei-Lin, C. and Beveridge, M.C.M., 1993. Shrimp culture and the environment - lessons from the world's most rapidly expanding warmwater aquaculture sector. In: R.S.V. Pullin, H. Rosenthal and J.L. Maclean (Editors), Environment and Aquaculture in Developing Countries. ICLARM Conference Proceedings, 31: 171-197.

Rubel and Hager Inc., 1979. Preliminary solids removal study. Rubel and Hager, Inc., 4400 E. Broadway, Tuscon, AR.

Teichert-Coddington, D., 1996. Management and effluent quality of semi-intensive shrimp farms. In: Proceedings of the 1996 Annual Meeting of the World Aquaculture Society, Bangkok, Thailand, p.401.

Tiensongrusmee, B., Gavine, F. and Phillips, M.J., 1996. Development of a management plan and effluent standards for coastal aquaculture in Thailand: Methodology and preliminary results. In: Proceedings of the 1996 Annual Meeting of the World Aquaculture Society, Bangkok, Thailand, p.406.

Wyban, J.A., Sweeney, J.N. and Kanna, R.A., 1988. Shrimp yields and economic potential of intensive round pond systems. J. World Aquacult. Soc., 19: 210-217.

Funge-Smith, S.J., 1996. Coastal aquaculture - strategies for sustainability. Final report to the ODA, Project R6011. Institute of Aquaculture, University of Stirling, Scotland.

Funge-Smith, S.J. and Briggs, M.R.P., (in prep). Water quality and nutrient discharge of intensive marine shrimp ponds in Thailand and their relationship to pond productivity. submitted to Aquaculture.

Hopkins,S.J., Sandifer, P.A. and Browdy, C.L.,1994. Sludge management in intensive pond culture of shrimp: Effect of management regime on water quality, sludge characteristics, nitrogen extinction and shrimp production. Aquaculture Engineering, **13**, 11-30.

Hopkins,S.J., Sandifer, P.A. and Browdy, C.L.,1995. A review of water management regimes which abate the environmental impacts of shrimp farming. In: (C.L. Browdy and J.S. Hopkins eds) Swimming through troubled waters. Proceedings of the special session on shrimp farming. Aquaculture '95. World Aquaculture Society, Baton Rouge, Louisiana,USA. 157 - 166

Kirchman, D.L. and Ducklow, H.W., 1987. Trophic dynamics of particle bound bacteria in pelagic ecosystems. In: D. J.W. Moriarty and R.S.V. Pullin (Editors), Detritus and Microbial Ecology in Aquaculture, ICLARM conference proceedings 14, 420p. ICLARM,Manila, Philippines.

Lin, C.K., 1989. Prawn culture in Taiwan. What went wrong ? World Aquaculture, 20(2): 19-20.

NACA, 1994. The environmental management of coastal aquaculture. An assessment of shrimp culture in southern Thailand. Final report to the Office of Environmental Policy and Planning. Network of Aquaculture Centres in Asia-Pacific. January 1994.

Phillips, M.J., Kwei-Lin, C. and Beveridge, M.C.M., 1993. Shrimp culture and the environment - lessons from the world's most rapidly expanding warmwater aquaculture sector. In: R.S.V. Pullin, H. Rosenthal and J.L. Maclean (Editors), Environment and Aquaculture in Developing Countries. ICLARM Conference Proceedings, 31: 171-197.

Rubel and Hager Inc., 1979. Preliminary solids removal study. Rubel and Hager, Inc., 4400 E. Broadway, Tuscon, AR.

Teichert-Coddington, D., 1996. Management and effluent quality of semi-intensive shrimp farms. In: Proceedings of the 1996 Annual Meeting of the World Aquaculture Society, Bangkok, Thailand, p.401.

Tiensongrusmee, B., Gavine, F. and Phillips, M.J., 1996. Development of a management plan and effluent standards for coastal aquaculture in Thailand: Methodology and preliminary results. In: Proceedings of the 1996 Annual Meeting of the World Aquaculture Society, Bangkok, Thailand, p.406.

Wyban, J.A., Sweeney, J.N. and Kanna, R.A., 1988. Shrimp yields and economic potential of intensive round pond systems. J. World Aquacult. Soc., 19: 210-217.

Table 4

Time (mth)	Open system Lined ponds	Open system Clay soil	Open system Mangrove soil	Semi-closed system	Closed system
	pH				
1	8.41 ± 0.39	8.63 ± 0.27	7.81 ± 0.71	8.59 ± 0.39	8.39 ± 0.48
2	7.83 ± 0.54	8.34 ± 0.42	7.94 ± 0.57	8.57 ± 0.35	8.50 ± 0.44
3	7.95 ± 0.28	8.34 ± 0.37	8.02 ± 0.41	8.69 ± 0.45	8.30 ± 0.20
4	7.65 ± 0.08	8.29 ± 0.84	7.82 ± 0.39	7.98 ± 0.47	8.00 ± 0.44
	Dissolved oxygen ($mg.l^{-1}$)				
1	3.84 ± 0.65	6.91 ± 1.70	4.20 ± 0.30	7.34 ± 1.89	8.09 ± 2.00
2	4.55 ± 1.01	7.24 ± 1.82	4.40 ± 2.12	8.43 ± 3.09	6.75 ± 1.36
3	4.17 ± 0.64	6.69 ± 1.80	3.83 ± 1.37	7.69 ± 2.46	7.64 ± 2.67
4	4.69 ± 1.41	7.15 ± 2.12	4.13 ± 0.64	7.67 ± 1.14	5.99 ± 2.22
	Total Ammonia-N ($mg.l^{-1}$)				
1	0.36 ± 0.24	0.02 ± 0.01	0.57 ± 0.35	0.95 ± 0.59	0.35 ± 0.14
2	1.03 ± 0.55	0.30 ± 0.41	1.45 ± 1.00	0.91 ± 0.38	0.97 ± 0.59
3	0.75 ± 0.52	0.82 ± 1.16	1.77 ± 0.59	1.56 ± 1.00	3.00 ± 1.20
4	1.06 ± 0.37	1.23 ± 1.39	2.08 ± 0.51	1.43 ± 0.67	2.63 ± 0.68
	Nitrite-N ($mg.l^{-1}$)				
1	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.10 ± 0.11	0.01 ± 0.01
2	0.01 ± 0.01	0.01 ± 0.01	0.04 ± 0.03	0.07 ± 0.06	0.05 ± 0.05
3	0.05 ± 0.04	0.01 ± 0.06	0.06 ± 0.03	0.13 ± 0.08	0.44 ± 0.26
4	0.41 ± 0.11	0.05 ± 0.08	0.11 ± 0.05	0.29 ± 0.16	0.29 ± 0.18
	Nitrate-N ($mg.l^{-1}$)				
1	0.06 ± 0.04	0.08 ± 0.08	0.03 ± 0.02	0.22 ± 0.22	0.06 ± 0.06
2	0.07 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.16 ± 0.15	0.09 ± 0.09
3	0.06 ± 0.03	0.04 ± 0.05	0.09 ± 0.02	0.16 ± 0.13	0.27 ± 0.45
4	0.40 ± 0.26	0.10 ± 0.05	0.18 ± 0.11	0.25 ± 0.26	0.27 ± 0.34
	Total Phosphorus ($mg.l^{-1}$)				
1	0.30 ± 0.11	0.21 ± 0.08	0.13 ± 0.03	0.19 ± 0.04	0.20 ± 0.09
2	0.41 ± 0.04	0.38 ± 0.16	0.24 ± 0.13	0.30 ± 0.06	0.35 ± 0.07
3	0.68 ± 0.13	0.31 ± 0.08	0.45 ± 0.09	0.31 ± 0.09	0.48 ± 0.12
4	0.79 ± 0.14	0.31 ± 0.12	0.72 ± 0.12	0.37 ± 0.09	0.40 ± 0.16
	Dissolved Reactive Phosphorus ($mg.l^{-1}$)				
1	n.d.	0.05 ± 0.07	n.d.	0.03 ± 0.02	0.02 ± 0.01
2	n.d.	0.04 ± 0.05	n.d.	0.02 ± 0.01	0.03 ± 0.01
3	n.d.	0.02 ± 0.02	n.d.	0.01 ± 0.01	0.05 ± 0.02
4	0.06 ± 0.03	0.02 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.04 ± 0.03
	Chlorophyll a ($\mu g.l^{-1}$)				
1	17 ± 7	19 ± 5	17 ± 16	45 ± 29	39 ± 22
2	66 ± 23	68 ± 13	66 ± 45	106 ± 48	67 ± 25
3	139 ± 44	94 ± 21	147 ± 60	134 ± 50	158 ± 50
4	105 ± 35	175 ± 18	175 ± 116	88 ± 23	86 ± 70
	Chemical Oxygen Demand ($mg.O_2.l^{-1}$)				
1	5.6 ± 1.0	n.d.	5.1 ± 0.8	4.2 ± 0.5	5.3 ± 0.6
2	6.6 ± 1.0	n.d.	6.7 ± 1.5	6.1 ± 0.7	6.5 ± 0.6
3	9.2 ± 0.4	n.d.	8.4 ± 0.5	6.5 ± 1.0	7.7 ± 0.8
4	9.2 ± 0.3	n.d.	8.7 ± 0.4	6.0 ± 0.7	7.0 ± 1.0
	Total Suspended Solids ($mg.l^{-1}$)				
1	72 ± 5	100 ± 23	77 ± 17	93 ± 28	116 ± 52
2	99 ± 13	159 ± 25	98 ± 26	152 ± 68	183 ± 32
3	144 ± 28	147 ± 41	139 ± 18	154 ± 56	173 ± 67
4	114 ± 26	169 ± 43	114 ± 52	142 ± 29	135 ± 73
	Organic Matter Content of Total SuspendedSolids (%)				
1	44 ± 6	27 ± 1	39 ± 4	28 ± 9	30 ± 10
2	37 ± 6	28 ± 3	30 ± 8	36 ± 9	32 ± 4
3	33 ± 6	29 ± 3	29 ± 5	35 ± 10	32 ± 4
4	34 ± 9	30 ± 2	27 ± 5	28 ± 4	34 ± 9

Figures

Fig. 1 Pondwater TAN concentrations during production from different types of intensive shrimp ponds in southern Thailand

Fig. 2 Pondwater Nitrite-N concentrations during production from different types of intensive shrimp ponds in southern Thailand

Fig. 3 Pondwater Nitrate-N concentrations during production from different types of intensive shrimp ponds in southern Thailand

Fig. 4 Pondwater Total phosphorus concentrations during production from different types of intensive shrimp ponds in southern Thailand

Fig. 5 Pondwater Dissolved reactive phosphorus (DRP) concentrations during production from different types of intensive shrimp ponds in southern Thailand

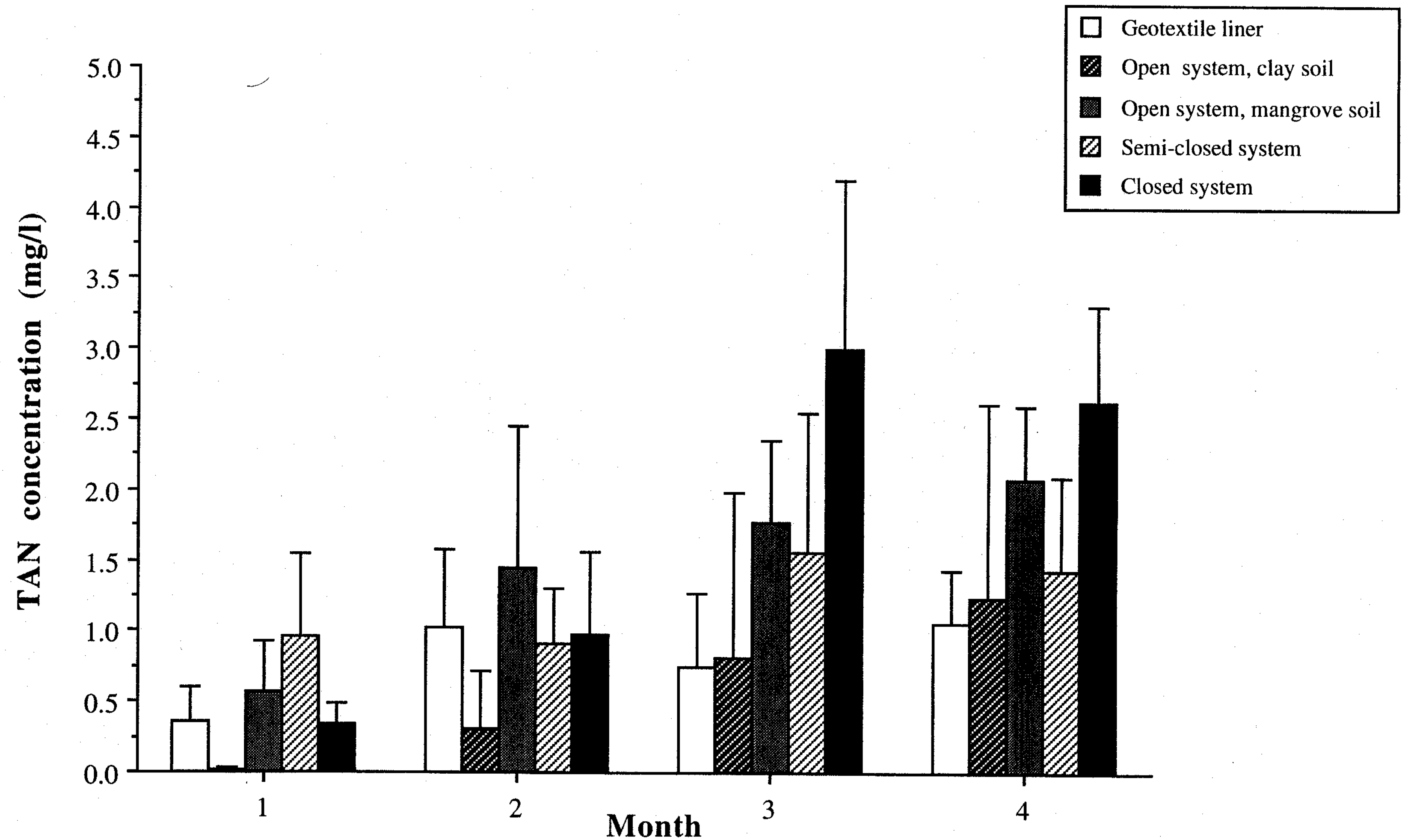
Fig. 6 Pondwater Chlorophyll a concentrations during production from different types of intensive shrimp ponds in southern Thailand

Fig. 7 Pondwater Chemical oxygen demand (COD) concentrations during production from different types of intensive shrimp ponds in southern Thailand

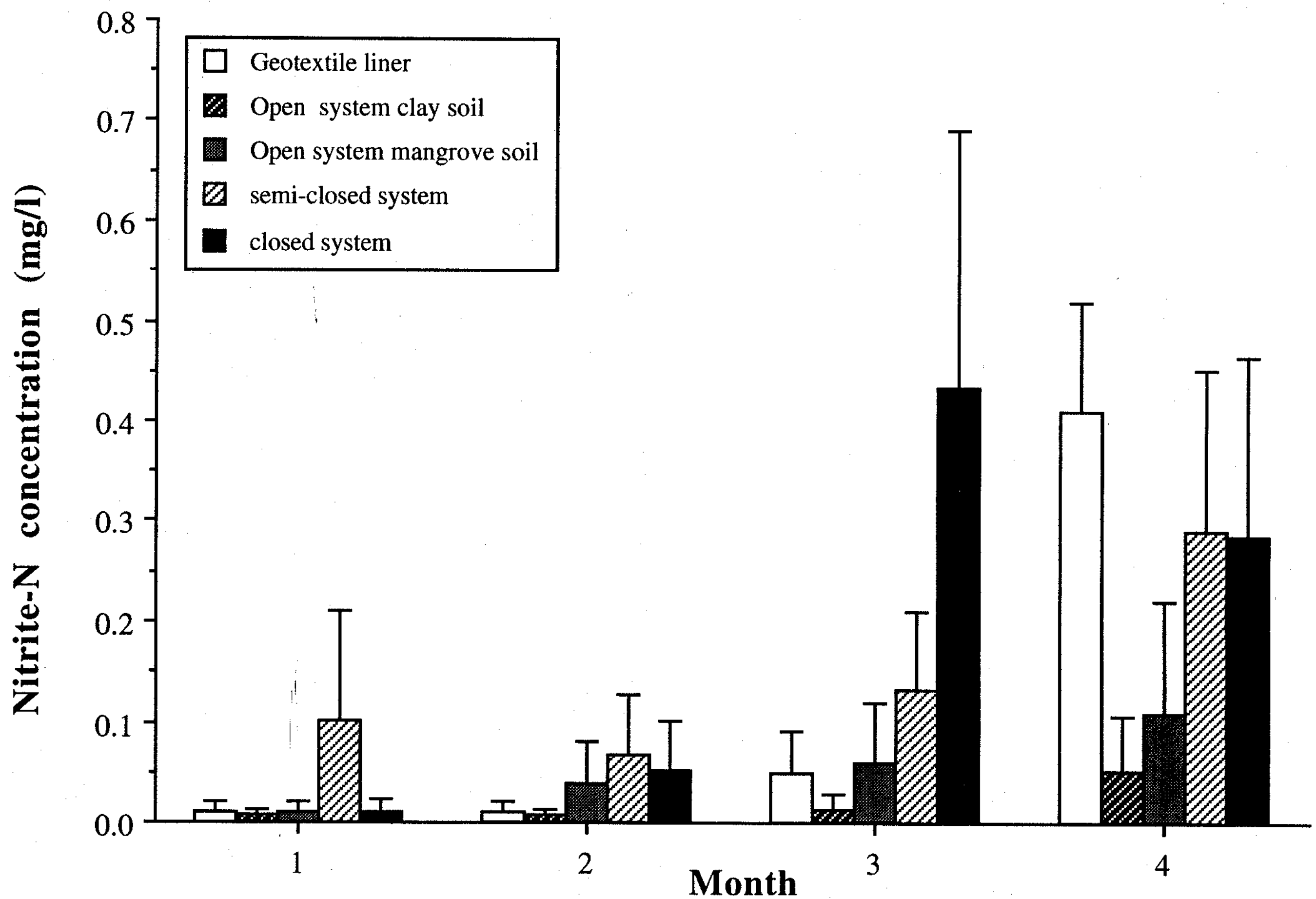
Fig. 8 Pondwater Total suspended solids concentrations during production from different types of intensive shrimp ponds in southern Thailand

Fig. 9 Pondwater Percentage organic content of total suspended solids concentrations during production from different types of intensive shrimp ponds in southern Thailand

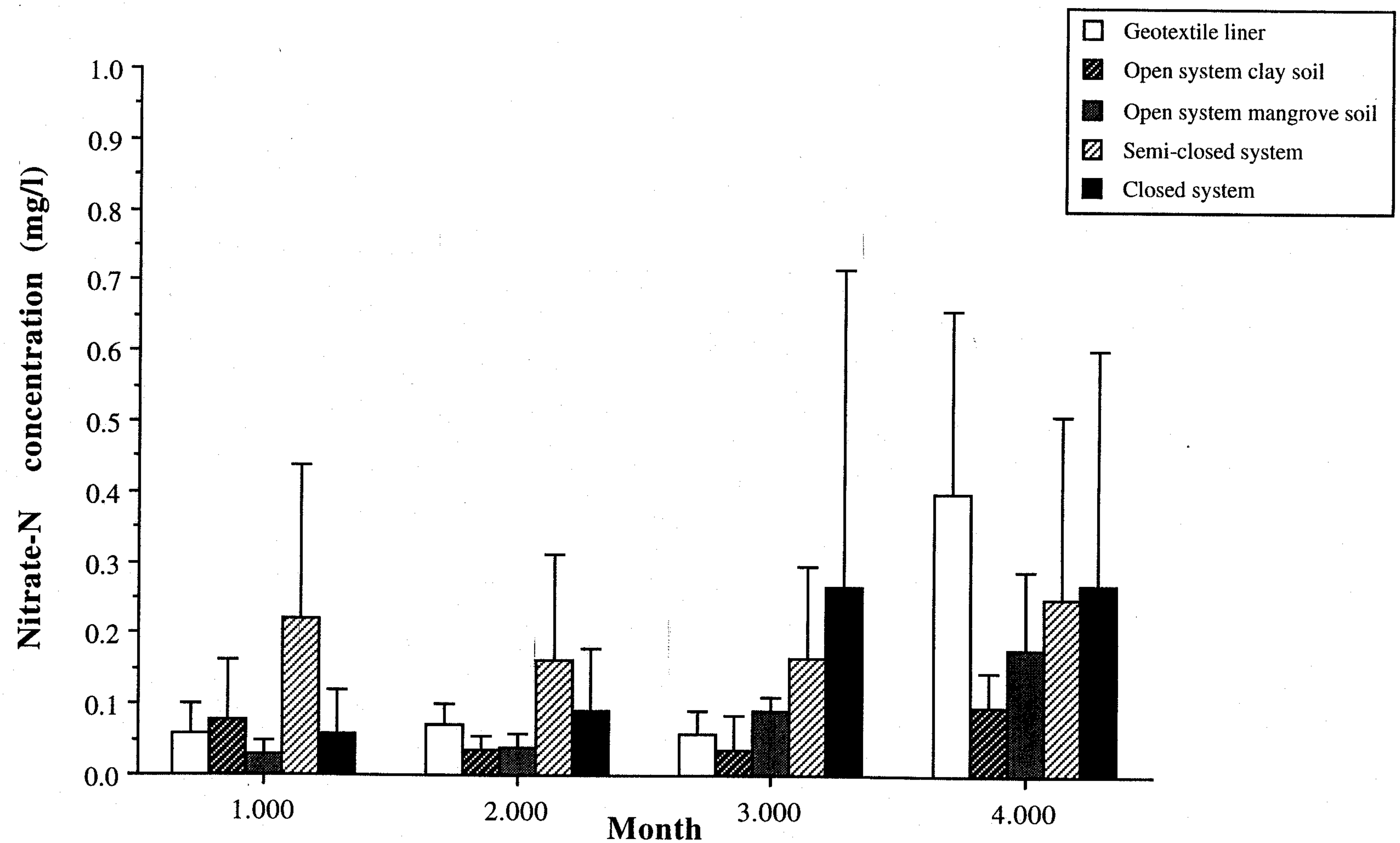
Pondwater TAN concentrations during production from different types of intensive shrimp ponds in southern Thailand



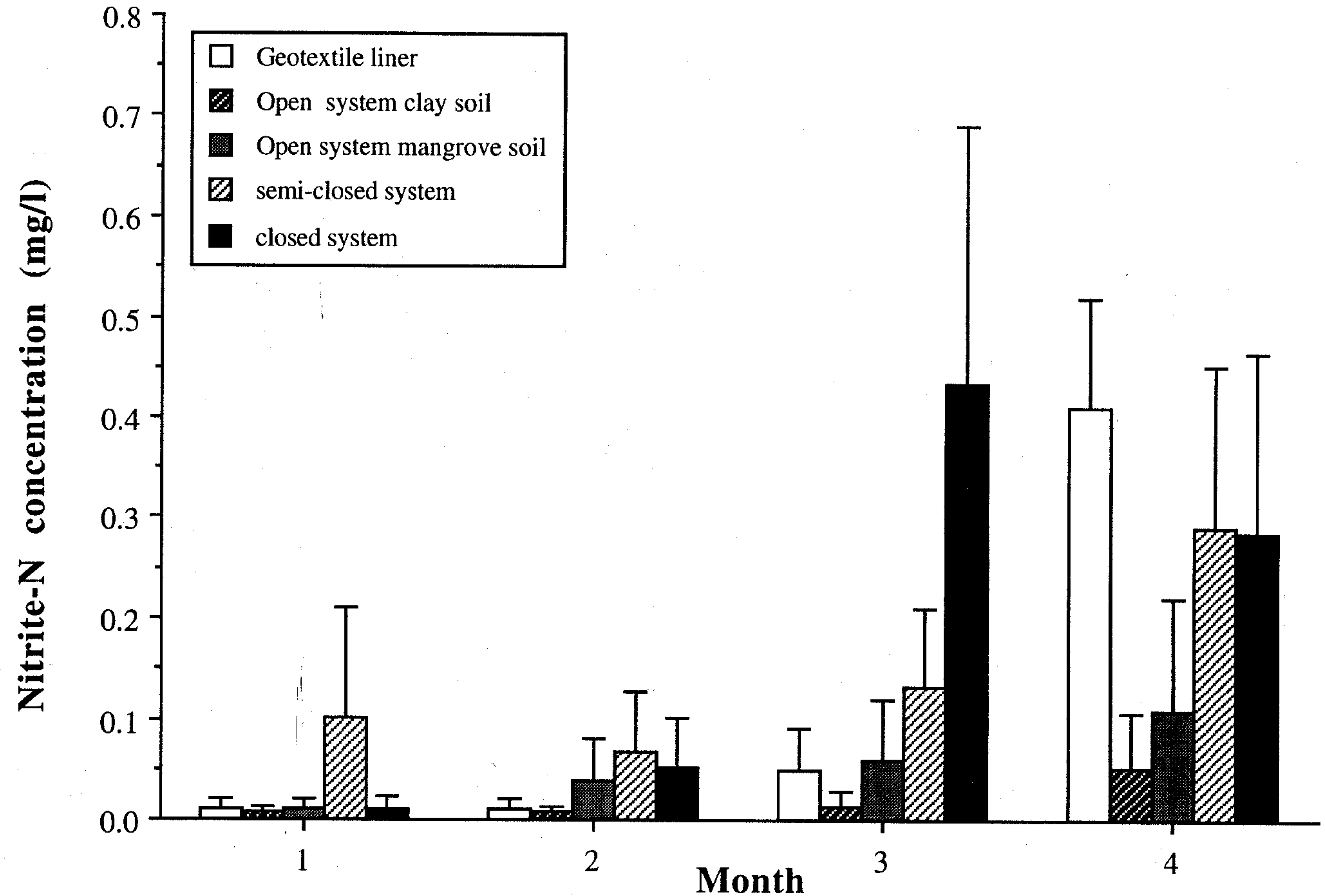
Pondwater Nitrite-N concentrations during production from different types of intensive shrimp ponds in southern Thailand



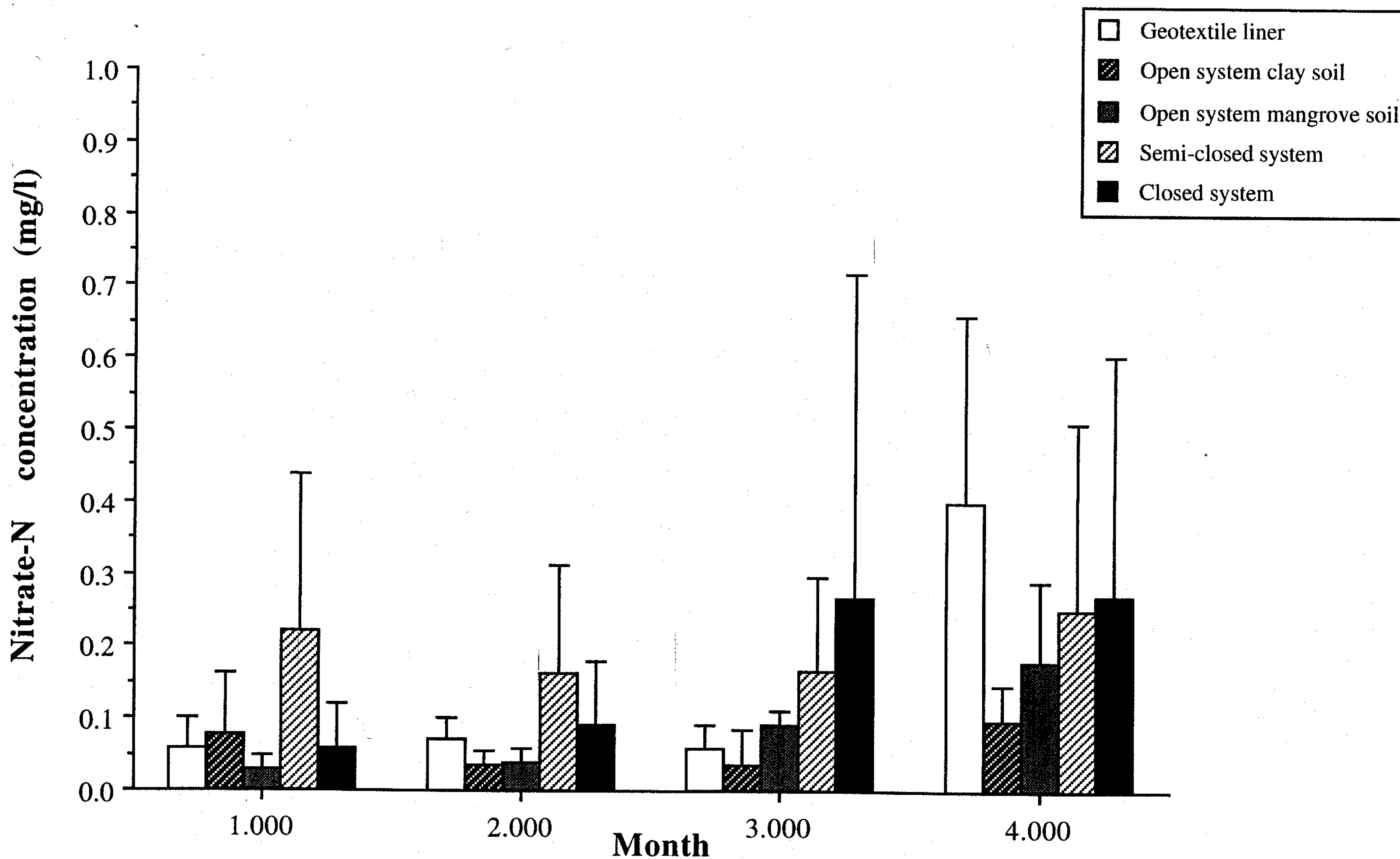
Pondwater Nitrate-N concentrations during production from different types of intensive shrimp ponds in southern Thailand



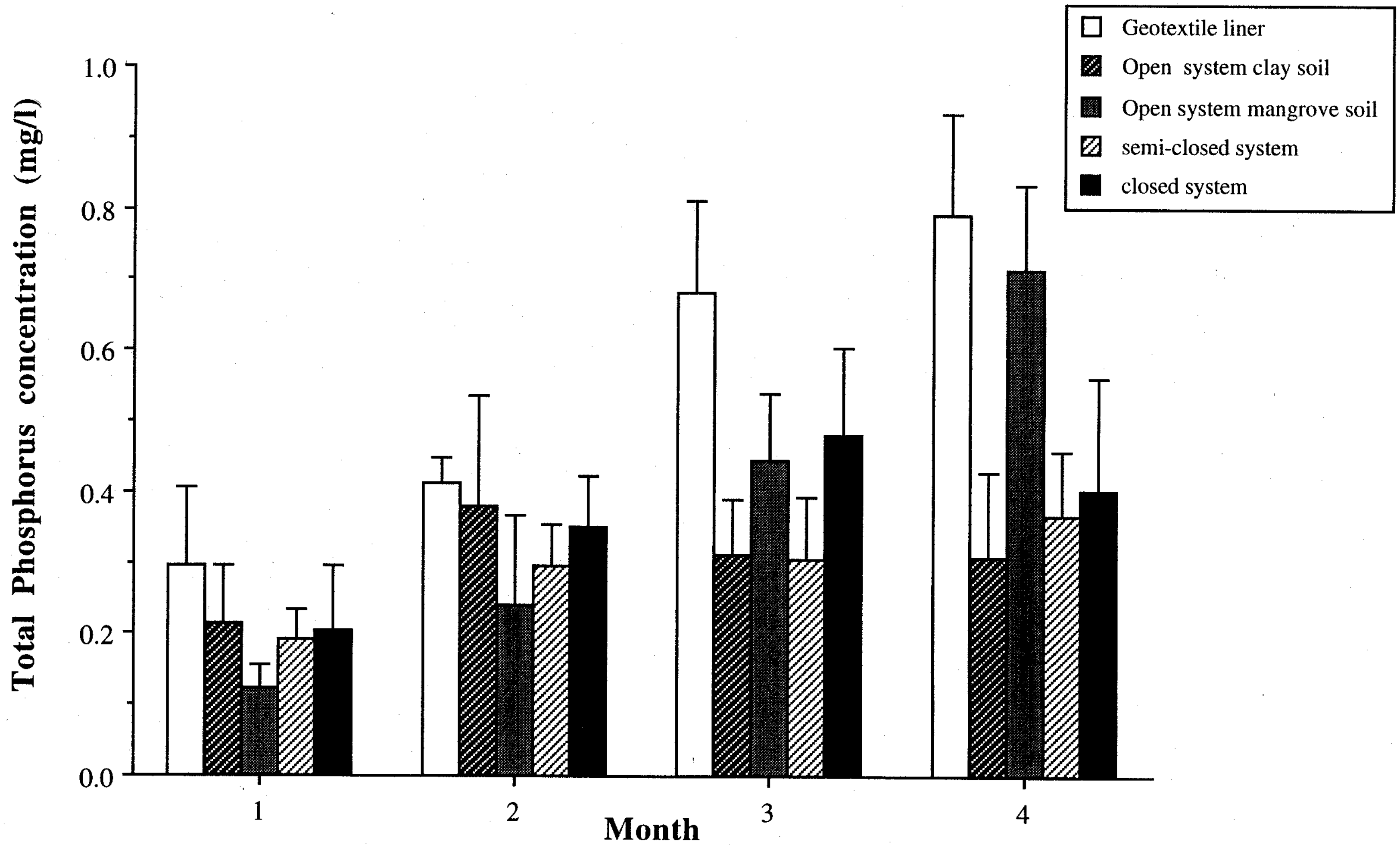
Pondwater Nitrite-N concentrations during production from different types of intensive shrimp ponds in southern Thailand



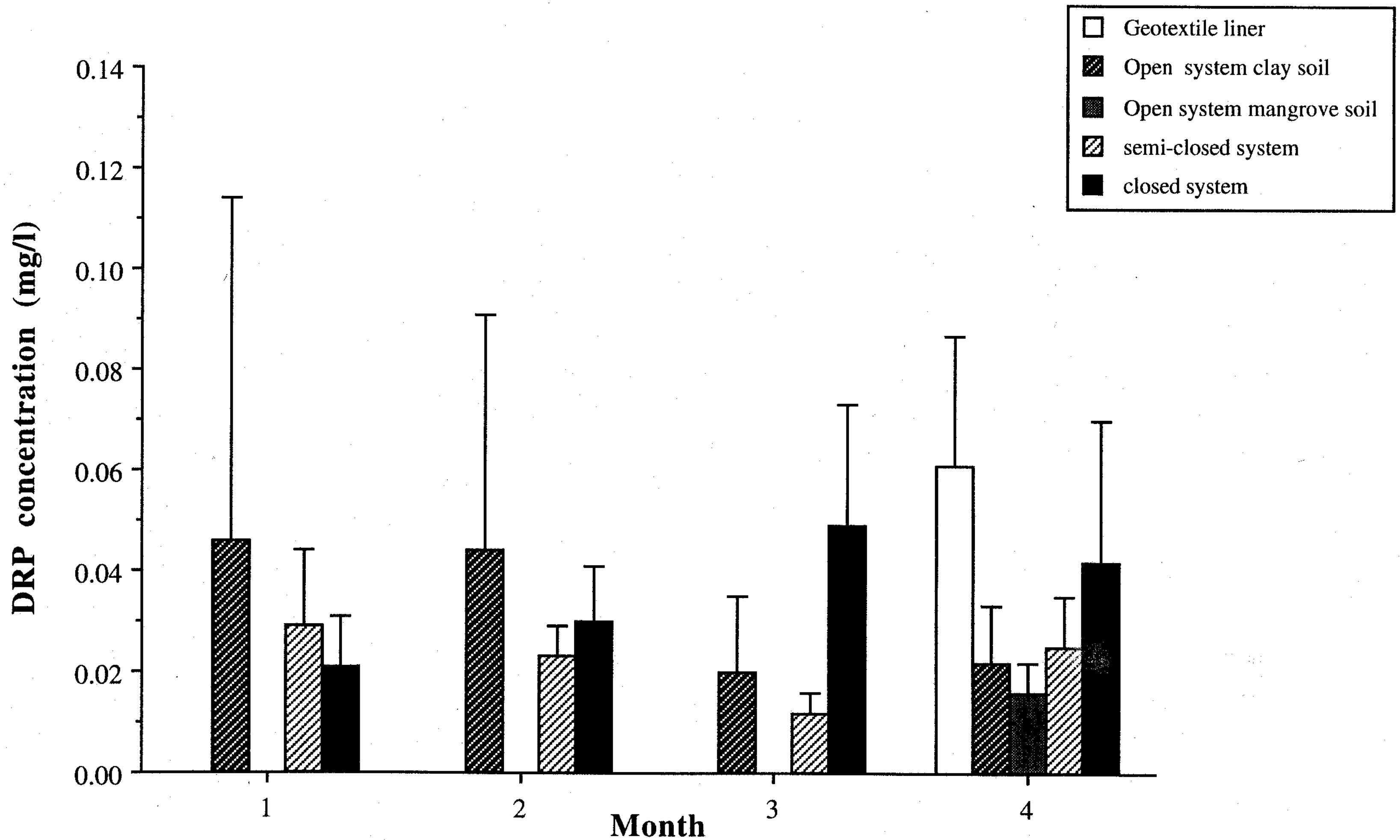
Pondwater Nitrate-N concentrations during production from different types of intensive shrimp ponds in southern Thailand



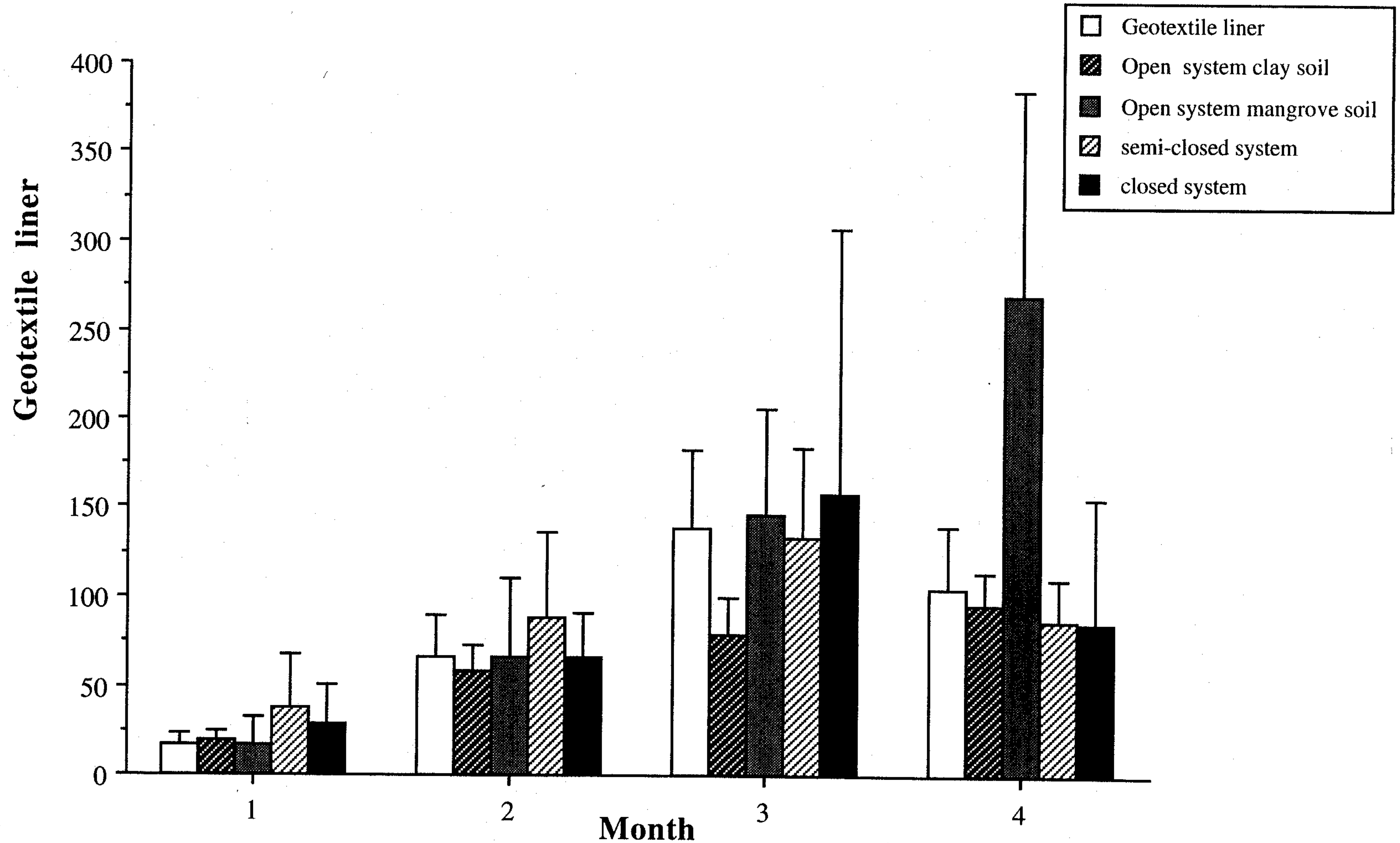
Pondwater Total phosphorus concentrations during production from different types of intensive shrimp ponds in southern Thailand



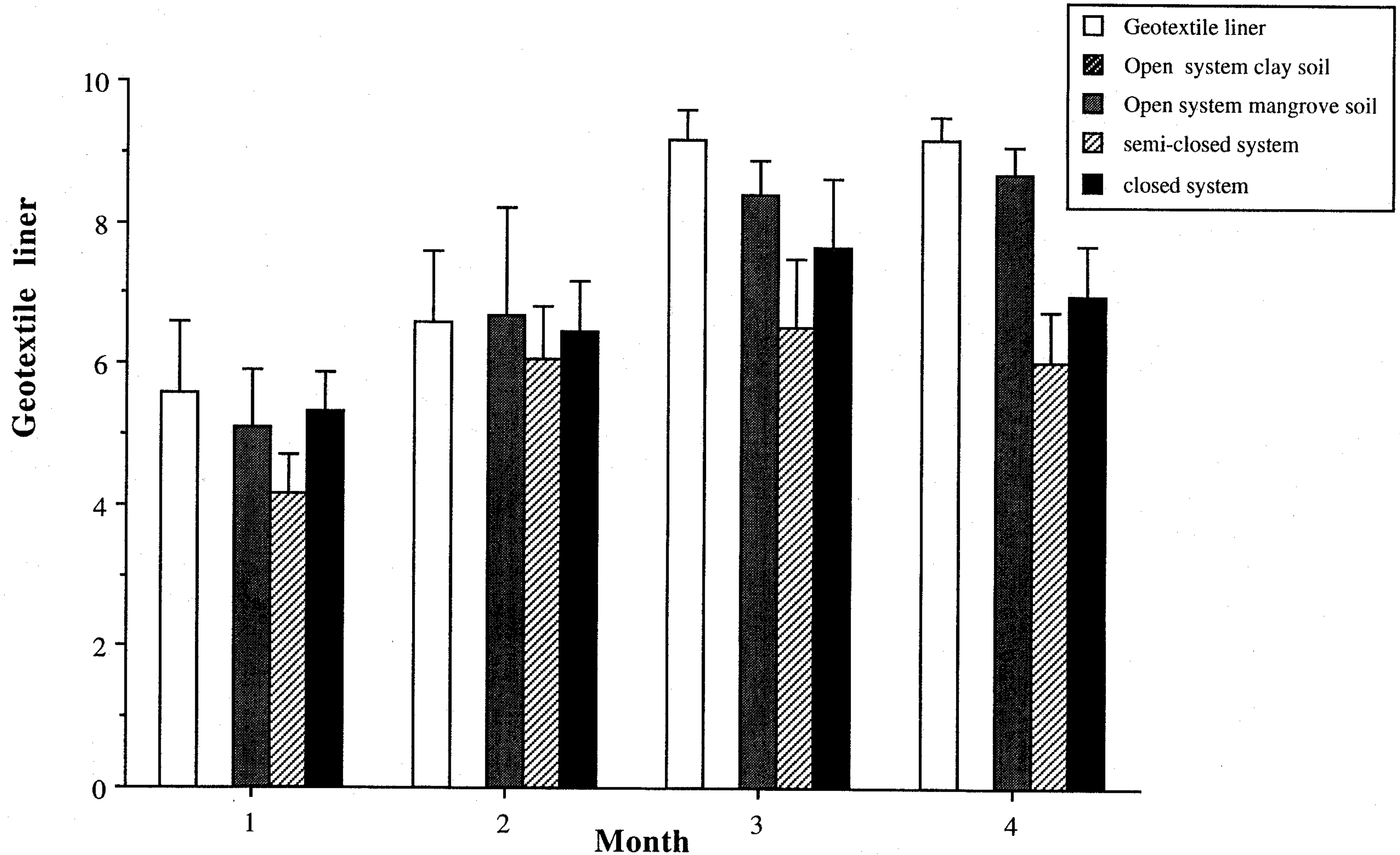
Pondwater DRP concentrations during production from different types of intensive shrimp ponds in southern Thailand



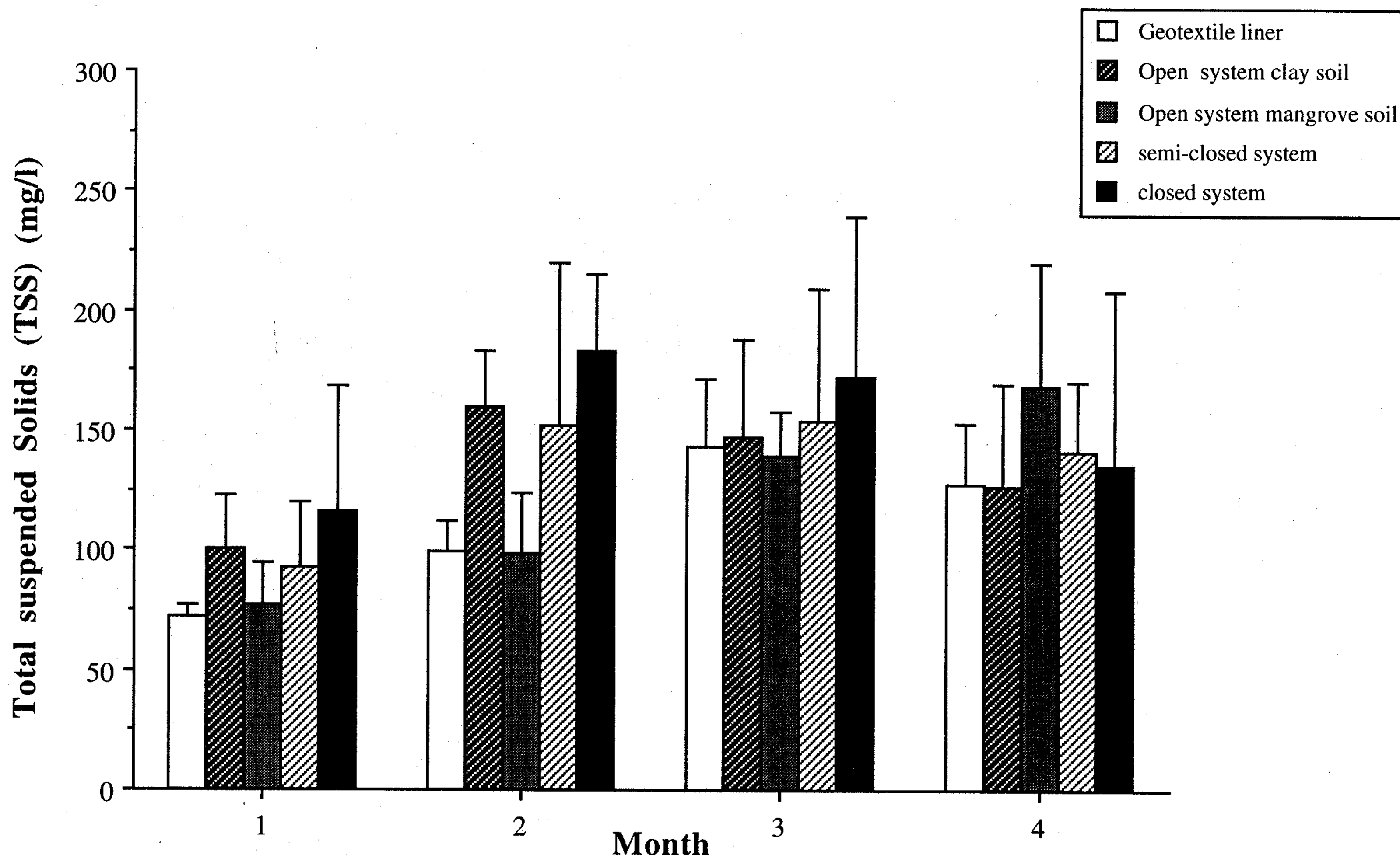
Pondwater chlorophyll a concentrations during production from different types of intensive shrimp ponds in southern Thailand



Pondwater Chemical Oxygen Demand during production from different types of intensive shrimp ponds in southern Thailand



Pondwater Total Suspended Solids concentrations during production from different types of intensive shrimp ponds in southern Thailand



Percentage organic matter in pondwater suspended solids during production from different types of intensive shrimp ponds in southern Thailand