46

Upgrading facultative wastewater lagoons with vascular aquatic plants

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Human waste disposal problems have been the focus of attention for a number of years, but now, with the population increasing rapidly, more stringent controls over waste materials are urgently needed to protect our potable and recreational waters. A primary goal of waste treatment management is to develop more efficient systems of waste stabilization, leading ultimately to water purification and recycling.

The effectiveness of waste treatment systems is measured by the reduction of oxygen demanding material [5-day biochemical oxygen demand (BOD_5)], total suspended solids (TSS), and nutrients such as nitrogen and phosphorus that are discharged into receiving waters. The Environmental Protection Agency (EPA) has recently set stricter standards on discharges from wastewater treatment facilities. As of July 1, 1977, treatment must effect an 85% removal of both BOD_5 and TSS. The maximum allowable level for both parameters is 30 mg/l.

In the United States, wastewater lagoons are the most popular and inexpensive method of treating domestic wastewater in small communities. According to Gloyna,[1] wastewater lagoons generally cost less than half as much as other treatment methods (provided that land costs are not excessive) and require a minimum of maintenance. According to Lewis,[2] approximately 90% of the wastewater lagoons in this country serve communities of 10 000 or less.

Domestic wastewater lagoons can be generally classified into three categories: anaerobic, aerobic, and facultative, which combines features of anaerobic and aerobic ponds. The design features of these ponds are discussed in detail by Oswald[3] and Gloyna.[1] In the southern United States the most commonly used design is that of the facultative wastewater lagoon.

Recently, Barsom[4] conducted a survey assessing the performance of wastewater lagoons throughout the U. S. This survey indicated that the majority of wastewater lagoons are not meeting EPA's July 1977 standards. According to this survey, the BOD_5 of facultative lagoons averaged 25 to 75 mg/l and TSS ranged from 60 to 210 mg/l. Although much of the suspended solids consists of algae, EPA standards do not differentiate between algae and other organics. Clearly, wastewater lagoons must be upgraded to meet EPA standards. As was stated in a recent EPA symposium, "the development of relatively inexpensive methods for upgrading lagoons that do not require sophisticated and constant operation or expensive maintenance is urgently needed" (Middlebrooks *et al.*[5]). According to these workers and Barsom,[4] effective reduction of algae and suspended solids in lagoon effluents is the highest priority research goal.

To understand why wastewater lagoons might fail to function properly, it is necessary to examine the processes that occur within these ponds. The overall principle of facultative lagoon operation is simple, relying upon the conversion of complex organics into bacteria, algae, and nutrients. The processes of synthesis and endogenous respiration carried on by algae and bacteria in lagoon systems are not thoroughly understood. However, we may simplify the natural purification of wastewater in facultative lagoons as follows: anaerobic and aerobic bacteria decompose organic waste through reduction and oxidation processes, respectively, producing carbon dioxide, methane, water, energy, and free nutrients. Algae use these nutrients in photosynthesis to generate oxygen and produce organic material in a form more compatible with the environment. Some of these algae are lost from the system in the effluent, some are consumed by aquatic grazers, and some die and are naturally degraded within the system. Effective lagoon operation requires that incoming nutrients and organic matter be broken down or removed from the system so that they do not appear in the effluent.

In general, properly designed wastewater lagoons operate efficiently for much of the year. During the winter, lagoon effluent is low in both BOD_5 and TSS because there is little biological activity or algal growth during this season. In the spring, however, as rising temperatures create conditions favorable for growth, the algae respond dramatically to the high level of nutrients which have been building up in the lagoon over the winter months, resulting in tremendous algal growth. Subsequent massive algal death creates a high oxygen demand, favoring the growth of anaerobic bacteria, which in turn often cause odor problems. Thus, spring and early summer are the seasons when lagoons are most likely to produce odors and/or effluents of unacceptable quality. The obvious solution to this problem is to reduce the amount of algae present in the lagoon during the spring and summer months.

Direct harvesting of algae is a costly and complicated procedure. To date, no methods for mechanical removal of algae, feasible for use in small communities, have been perfected, although several are in the testing stage (see Middlebrooks *et al.*[5]). Introducing a vascular aquatic plant species has been considered as one means of reducing the amount of algae in the lagoon effluent. Vascular aquatic plants could discourage erratic fluctuations in algal populations both by removing excess nutrients and by shading the algae from sunlight. Several investigators[6-9] have proposed using the water hyacinth (*Eichhornia crassipes*) for these purposes. Water hyacinths, which remove both nutrients and organics directly from the water via their extensive root systems,[1, 10, 11] can increase at the phenomenal rate of 15% of their surface area per day, producing at least 19 wet metric tons/ha·d.[12] Based on measured growth rates, Rogers and David[13] estimated that 1 ha of water hyacinths could remove the nitrogen and phosphorus waste of over 800 people per day. These concentrated nutrients can then be removed from the system by harvesting the water hyacinths. The harvested plant material has potential economic value as a soil amendment,[14] as a livestock feed,[15] and perhaps even as a human protein supplement.[16, 17]

Another vascular aquatic plant capable of supplementing the role of the water hyacinth during the winter months is duckweed (*Lemna* and *Spirodela* spp.). Studies with these cold-tolerant plants have shown that they can thrive on domestic wastewater and also remove excess nutrients and produce a significant effect on BOD and TSS reduction rates.[18-20]

Since 1975, the National Aeronautics and Space Administration has been growing water hyacinths (*Eichhornia crassipes*) throughout most of the year and duckweed (*Lemna* and *Spirodela* spp.) during the winter in wastewater lagoons at the National Space Technology Laboratories (NSTL), Bay St. Louis, Miss., to improve effluent quality. In this report, the performance of one of these lagoons before and after the addition of water hyacinths and duckweed is traced.

DESCRIPTION OF THE SYSTEM

NSTL Lagoon #1 consists of a single cell with a surface area of approximately 2 ha and an average depth of 1.22 m. The average flow rate of 475 m^3/d results in a retention time of approximately 54 days. The BOD_5 loading rate in this lagoon averages 22 to 30 kg/ha·d, which constitutes a relatively light load.[3] Before the introduction of water hyacinths, the average suspended solids discharged in the effluent waters of this lagoon exceeded the EPA limit during some months of the spring and summer.

MATERIALS AND METHODS

Adequate background data on Lagoon #1 without water hyacinths necessary for comparison of BOD_5, TSS, and pH were recorded in the NSTL environmental monitoring files for the period of May to September 1974. During this period approximately two grab samples per week were analyzed. Only six samples were obtained during July 1974. Inasmuch as only one grab sample per month was analyzed as required by the EPA discharge permit effective during the intervening months of October 1974 to March 1976, the data was judged inadequate for comparative purposes and, therefore, omitted. During the background months used in this study, approximately 1 000 people were serviced by this lagoon. This population increased to 2 000 people by the summer of 1977 .

Beginning in March of 1976, influent and effluent grab samples were taken twice a week from the lagoon and analyzed for additional parameters. Water samples were analyzed for pH using a combination electrode, dissolved oxygen (DO) using the membrane electrode

TABLE I. Monthly average data of total suspended solids and 5-day biochemical oxygen demand for background and experimental periods.

Date	TSS, mg/l		BOD_5, mg/l	
	Influent	Effluent	Influent	Effluent
A. Background period				
May, 1974	130	88	83	17
June, 1974	60	76	54	25
July, 1974	40	51	61	17
August, 1974	47	46	83	23
September, 1974	50	27	92	13
March, 1976	78	17	138	9
April, 1976	77	50	93	16
May, 1976	75	39	122	14
B. Initial stocking months (partial water hyacinth coverage)				
June, 1976	112	25	79	9
July, 1976	63	12	70	5
C. Water hyacinth experimental period				
August, 1976	89	5	109	7
September, 1976	68	6	140	5
October, 1976	64	3	112	2
November, 1976	84	4	143	2
December, 1976[a]	113	8	90	2
January, 1977[a]	88	8	69	2
February, 1977[a]	132	14	88	7
March, 1977[b]	103	17	93	14
April, 1977[b]	116	17	97	9
May, 1977[b]	161	13	201	6
June, 1977	86	18	125	5
July, 1977	78	9	141	5
August, 1977	80	12	37	6
September, 1977	101	8	96	4

[a] Water hyacinths damaged by cold weather; duckweed treatment operative.
[b] Water hyacinths recover from winter with initial coverage of 20% in March, 1977.

method, temperature, suspended and dissolved solids using standard glass fiber filters to determine the filtrable and nonfiltrable residues, and BOD_5 using the membrane electrode method to determine the dissolved oxygen concentrations according to "Standard Methods." Total organic carbon (TOC) was determined with the combustion-infrared method using a TOC analyzer (Beckman 915). Kjeldahl nitrogen and phosphorus were determined with an autoanalyzer (Technicon) after sample digestion with a $H_2SO_4/K_2SO_4/Hg_2SO_4$ solution.

Water hyacinths were introduced into the lagoon in June 1976, and by August the plants had covered approximately 90% of the surface area. Most of the plants, which are not cold-tolerant, died during the winter months and were replaced by duckweed. In March 1977, the surviving plants resprouted, achieving a 25% coverage by the end of this month.

RESULTS

By comparing the quality of the lagoon's effluent during the background and experimental periods, a clear picture of the effects of water hyacinths and duckweeds can be seen. Table I presents all of the compiled data on TSS and BOD_5 for the available background and water hyacinth treatment periods. The data for suspended solids can be more easily examined in Figure 1. These vascular aquatic plants substantially reduced the suspended solids below the 30 mg/l maximum EPA level and reliably maintained this requirement all year. The substantial reduction of suspended solids was largely a result of the virtual elimination of algae from the system. Water hyacinths are the most effective in the summer

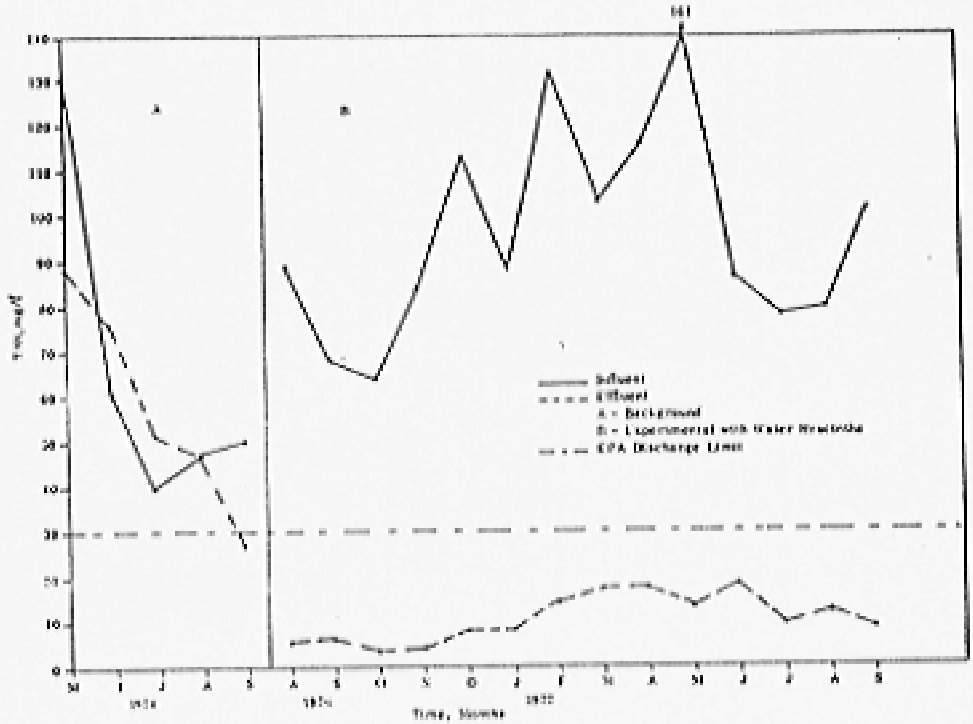

FIGURE 1. Monthly average total suspended solids versus time (months).

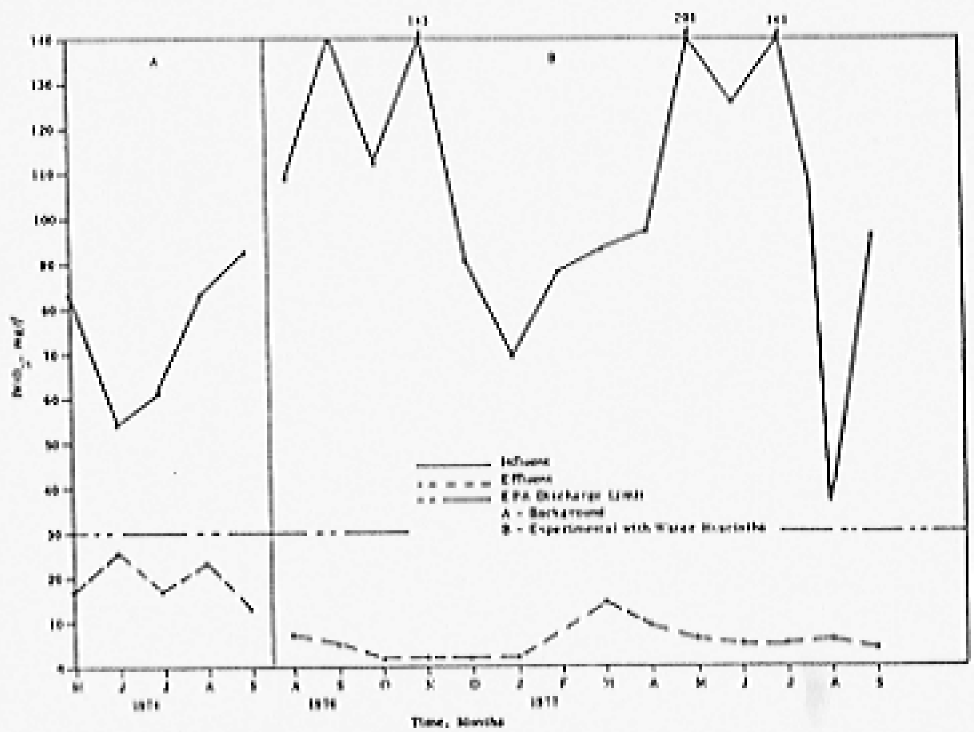

FIGURE 2. Monthly average BOD_5 versus time (months).

TABLE II. Comparative percent reductions of TSS and BOD_5.

	Percent Reduction			
	TSS		BOD_5	
Month	Without Water Hyacinths	With Water Hyacinths	Without Water Hyacinths	With Water Hyacinths
May	32/48[a]	92	80/89[a]	97
June	−27	79	54	96
July	−28	88	72	96
August	2	85/94[a]	72	94/84[a]
September	46	92/91[a]	86	96/96[a]

[a] Two consectuve year reductions.

months, which coincides with the maximum problem period for a lagoon. The percent reduction of

$$\text{TSS}\left(\frac{\text{INF. TSS} - \text{EFF. TSS}}{\text{INF. TSS}} \times 100\%\right)$$

was highly variable before the introduction of water hyacinths. As shown in Table II, the TSS in the effluent was often more than the influent during the summer months because of periodic algal blooms. However, with water

TABLE III. Monthly average data of pH and dissolved oxygen for background and experimental periods.

Date	pH Influent	pH Effluent	DO, mg/l Influent	DO, mg/l Effluent
A. Background period				
May, 1974	7.1	9.8	4.3	9.6
June, 1974	7.0	10.4	3.7	6.7
July, 1974	7.0	10.0	3.2	4.2
August, 1974	7.0	9.1	2.8	4.8
September, 1974	7.0	9.2	2.4	8.2
March, 1976	6.9	7.7	2.0	3.9
April, 1976	7.0	9.1	1.1	10.8
May, 1976	7.2	8.8	1.5	7.3
B. Initial stocking months (partial water hyacinth coverage)				
June, 1976	7.3	7.6	1.4	6.8
July, 1976	7.2	7.3	1.0	5.0
C. Water hyacinth experimental period				
August, 1976	7.4	7.2	1.1	2.4
September, 1976	7.2	7.0	1.0	0.6
October, 1976	7.2	7.0	0.9	1.5
November, 1976	7.2	7.2	1.5	2.9
December, 1976[a]	7.2	7.2	1.8	3.3
January, 1977[a]	7.0	7.1	1.7	3.5
February, 1977[a]	7.0	7.2	0.8	2.6
March, 1977[b]	7.0	7.1	1.1	2.0
April, 1977[b]	6.9	7.1	1.0	2.3
May, 1977[b]	7.1	7.2	0.7	2.7
June, 1977	7.5	7.2	1.0	2.3
July, 1977	7.1	6.9	1.0	1.8
August, 1977	7.1	6.9	1.2	1.9
September, 1977	7.0	7.1	1.1	1.8

[a] Water hyacinths damaged by cold weather; duckweed treatment operative.
[b] Water hyacinths recover from winter with initial coverage of 20% in March, 1977.

TABLE IV. Monthly average total Kjeldahl nitrogen, total phosphorus, and total organic carbon for background and experimental periods. (Background data on these parameters not available for May 1974–September 1974.)

Date	TKN, mg/l		TP, mg/l		TOC, mg/l	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
A. Background Period						
March, 1976	9.9	7.4	3.1	1.9	62	20
April, 1976	8.8	4.4	2.9	2.1	65	37
May, 1976	10.8	3.8	2.8	2.2	38	38
B. Initial stocking months (partial water hyacinth coverage)						
June, 1976	8.2	2.6	2.3	1.7	43	34
July, 1976	7.8	1.9	2.2	0.9	33	19
C. Water hyacinth experimental period						
August, 1976	12.1	3.0	3.6	1.1	51	15
September, 1976	10.0	1.4	5.8	1.0	54	14
October, 1976	11.3	2.0	3.1	1.1	35	14
November, 1976	13.3	3.5	3.5	0.7	59	15
December, 1976[a]	10.7	3.0	1.8	1.0	36	15
January, 1977[a]	12.7	4.1	2.6	1.2	56	14
February, 1977[a]	15.5	5.4	4.0	2.6	72	29
March, 1977[b]	13.7	5.1	4.6	2.8	59	24
April, 1977[b]	14.3	3.4	4.5	2.1	61	19
May, 1977[b]	15.2	1.9	4.9	1.8	62	12
June, 1977	13.2	2.3	3.7	1.8	49	15
July, 1977	8.4	2.6	3.3	1.8	44	17
August, 1977	8.5	3.9	3.3	1.4	34	17
September, 1977	9.3	5.3	3.6	1.5	89	19

[a] Water hyacinths damaged by cold weather; duckweed treatment operative.
[b] Water hyacinths recover from winter with initial coverage of 20% in March, 1977.

hyacinths present, TSS were consistently reduced by an average of 89%.

These vascular aquatic plants also had a significant effect on the reduction of BOD_5. This reduction was not as dramatic as the one with suspended solids because the lagoon was fairly effective at BOD_5 reduction before the introduction of aquatic plants. Figure 2 clearly shows that this aquatic plant system reliably maintains the BOD_5 all year below the EPA discharge limit of 30 mg/l. Table II shows that the lagoon achieved an average of 76% reduction in BOD_5 before water hyacinths were introduced; with aquatic plants, the lagoon reduced the BOD_5 by an average of 94%.

From Table III, the effect of these vascular aquatic plants on pH and DO can be ascertained. During the background period, the influent and effluent pHs averaged 7.0 and 9.3, respectively. The effluent pH often increased over 10. The EPA discharge permit limits the effluent pH to 9.0; therefore, it is clear that the lagoon rarely met this requirement. After the introduction of water hyacinths and duckweeds, the influent and effluent pHs averaged 7.1 each. This buffering effects results from an increase in CO_2 which is normally depleted during algal photosynthesis because algae derive all of their CO_2 from the wastewater, whereas most of the CO_2 required by water hyacinths is obtained from the air.

As expected, water hyacinths decreased the DO from an average effluent level of 6.9 mg/l without hyacinths to 2.3 mg/l with hyacinths (Table III). This would be critical to lagoon operation only if the lagoon were heavily loaded and anaerobic conditions prevailed. Minimum aeration could be applied at the discharge point to bring the effluent DO concentration up to the normally required level of 5 mg/l.

The available background data on total Kjeldahl nitrogen, total phosphorus and TOC concentrations is extremely limited (Table IV). These parameters were greatly reduced as shown in Table V in the summer months, with somewhat less reductions during the winter when duckweed is the dominant aquatic plant. Further interpretation of these results is difficult without a direct comparison, inasmuch as a significant quantity of nitrogen is normally lost from a lagoon as a result of natural denitrification processes. The high percentage reduction in TOC is largely because of the virtual elimination of algae as demonstrated by the dramatic reduction of suspended solids.

DISCUSSION

Results indicate that when water hyacinths assume a primary role in a wastewater lagoon, the operation of the system is significantly altered. The algal community, with its fast turnover rate and rapid succession, is replaced by a rapidly growing macrophyte that continuously converts dissolved organics and nutrients into a standing biomass which is not rapidly recycled and does not contribute to the TOC of the system. The hyacinth plant biomass, which remains within the system, is not present in the effluent. As a result, effluent from a hyacinth-covered lagoon will be lower in suspended solids, BOD_5, and nutrients.

Although water hyacinths are far superior to algae in a lagoon system, there are several disadvantages which should be recognized. As oxygen produced by the water hyacinth in photosynthesis does not significantly contribute to the oxidation process occurring within the lagoon, the anaerobic portion of a facultative lagoon may increase and, under conditions of heavy BOD loading, become total. Although water hyacinths are not affected by these conditions, odor problems may result. Therefore, when water hyacinth coverage is complete and BOD loading heavy, mechanical aeration of the lagoon may be necessary during photosynthetically inactive periods to prevent foul odors.

Another limitation of water hyacinths is that their use without protection is restricted to the warmer months of the year. In late autumn, the effectiveness of the water hyacinth is greatly reduced unless the plants are protected by greenhouses or by heating the influent. If unprotected, water hyacinths should be harvested following the first hard frost in the autumn. In our lightly loaded lagoon system, it was not necessary to harvest the hyacinths after one season of operation; however, for moderately to heavily loaded lagoons, the accumulated dead plant material would impose a large additional organic load; therefore, the plants should be harvested each fall. Fortunately, the water hyacinth's seasonal demise corresponds with general periods of low biological activity within the lagoon, in which TSS and organics are at the lowest concentrations. During cooler weather, winter-resistant primary producers such as duckweed (*Lemna* and *Spirodela* spp.) have taken over in our lagoons performing a certain amount of purification.[18, 22]

Although the necessity of periodic harvesting of the water hyacinths adds to the cost of operation of the lagoon system, these floating plants are much more easily harvested than submerged or rooted aquatics. We are optimistic over the prospect of selling the harvested hyacinths to recover at least a part of harvesting cost. Particularly promising is the use of hyacinths for cattle feed, plant compost, and biogas production. Nutrient analyses conducted by the authors,[22] for example, indicate that crude protein content of hyacinths grown in wastewater lagoons compares favorably with soybean and cottonseed meal, averaging 32.9% dry weight of leaves. Mara [23] estimated the value of selective water hyacinth by-products and concluded that the market was not sufficient to help defray the cost of mechanical control of water hyacinths. However, his analyses may not be applicable to water hyacinths harvested from wastewater lagoons for several reasons. Confinement of harvesting activities to a single location would minimize transportation and handling costs, thus increasing the economic feasibility of utilizing water hyacinth by-products. Locating dryers, choppers and other water hyacinth processing operations near the lagoon would further reduce processing and transportation costs. Also, when grown in nutrient-rich lagoon influent, the water hyacinth's growth rate is greatly enhanced. Scarsbrook and Davis [24] report a 15-

Table V. Average summer and winter percent reductions in total Kjeldahl nitrogen, total phosphorus, and total organic carbon with water hyacinths in summer and duckweeds in winter.

	Average Percent Reduction	
Parameter	Summer[a]	Winter[b]
TKN	73	67
TP	63	43
TOC	69	59

[a] Summer Months—April through November.
[b] Winter Months—December through March.

fold increase in dry matter production when hyacinths were grown in 25% wastewater effluent.

The most common insect which occasionally invades the water hyacinths is the spider mite (*Bryobia praetiosa*). Although this pest cannot eradicate the water hyacinth, it can cause extensive damage if not controlled. This insect is easily eliminated with a light application of malathion.

Mosquito breeding was not a problem in the NSTL lagoon. Because of the improved quality of the lagoon's water, *Gambusia affinis*, commonly referred to as mosquito-fish, flourished in the lagoon and naturally controlled mosquitos by feeding on the larvae.

In summary, these experiments have shown that substantial coverage of water hyacinths significantly upgrades effluent from a primary wastewater lagoon treating the waste of approximately 2 000 people. The addition of water hyacinths to a wastewater lagoon system not only reduces suspended solids and BOD_5, but also significantly decreases the nutrient and organic carbon content in the lagoon effluent. The use of vascular aquatic plants appears promising as an economical and efficient way of upgrading wastewater lagoon systems in small communities.

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