USE OF FLOATING VEGETATION TO REMOVE NUTRIENTS FROM SWINE LAGOON WASTEWATER

R. K. Hubbard, G. J. Gascho, G. L. Newton

ABSTRACT. *Methods are needed to remove nutrients contained within wastewater lagoons. Potential exists for nutrient removal directly from lagoons if vegetation can be grown on floating mats in the lagoon and periodically harvested and removed. Vegetative cover of lagoons may also help reduce odor problems. A study was conducted to determine the feasibility of using floating mats of vegetation on swine lagoon wastewater. Wastewater from the University of Georgia swine wastewater lagoons was pumped to replicated tanks (1285 L) in which floating mats of vegetation were grown. The floating platforms were made of PVC pipe with attached wire screen and fibrous material into which the vegetation was sprigged. Three different wetland species were tested: cattail (*Typha latifolia *L.), soft rush (*Juncus effuses*), and maidencane (*Panicum hematomon *Schult 'Halifax'). Full−strength wastewater, 1/2−strength wastewater, and an inorganic nutrient solution (1/4−strength Hoaglund solution) as a control were tested. The test was conducted as a modified batch process as opposed to a continuous flow through process. The modification was that every two weeks half of the volume of each tank was replaced with the appropriate solution of full−strength wastewater, 1/2−strength wastewater, or 1/4−strength Hoaglund solution so that nutrient concentrations would not be depleted. There were four replicate tanks of each nutrient solution for each wetland species, for a total of 36 tanks. Vegetation from the floating mats was harvested periodically by removing all vegetation above 5 cm of the base of the floating mat. Measurements were made at each cutting of the total biomass per tank, leaf area, and nutrient content (N, P, K) of the vegetative tissue. Growth responses were quite different among the three species. The cattail had tremendous growth during the spring and summer months. The growth rate of the rush was slow for the first year. It then died during summer of 2002 at both the 1/2−strength and full−strength wastewater, indicating that this species is not suitable for growth on floating mats in swine lagoon wastewater. Total nutrient removal by both the cattail and maidencane was primarily a function of total biomass produced. Over the length of the study, on full−strength wastewater, the cattail produced 16,511 g m^{-2} biomass and removed 534, 79, and 563 g m^{-2} of N, P, and K, respectively, while the maidencane produced 9751 g m^{-2} of biomass and removed 323, 48, and 223 g m^{-2} of N, P, and K, respectively. Results from this study indicate that potential exists for using floating platforms to grow cattail, maidencane, or possibly other yet to be identified plant species in wastewater lagoons for nutrient removal.*

Keywords. *Biomass production, Floating vegetative mats, Nutrient uptake, Wastewater lagoon, Wetland plant species.*

A number of methods have been designed to handle animal wastes from confined animal feeding operations (CAFOs). Most systems involve primary treatment in wastewater lagoons for settling of solids and loss of gases by volatilization. Anaerobic treatment systems (lagoons) are used widely for practical treatment and storage of swine manure (USDA Soil Conservation Service, 1992; Westerman et al., 1990). These lagoons are typically earthen and rely on bacteria to stabilize organic material (Pork Industry Handbook, 1998). Lagoons are relatively simple to operate and maintain, and are relatively inexpensive compared with other treatment methods (*ASAE Standards*, 1997).

Wastewater from lagoons generally is land applied. Land treatment systems may include application of wastewater to crops or pasture (Hatfield et al., 1998; Di et al., 1999; Newton et al., 2003), forest, vegetative buffer systems (Atwill et al., 2002; Hubbard et al., 1998, 2003), or constructed wetlands (Cronk and Mitsch, 1993). Newton et al. (2003) showed that dairy lagoon wastewater could be successfully used for triple cropping systems including both cropland and winter grazing of pasture. Hubbard et al. (1998) showed that vegetated buffer systems can effectively assimilate N from swine lagoon wastewater.

A number of authors (Breen 1990; Surrency, 1993) have shown that constructed wetlands can effectively utilize nutrients from lagoon wastewater. Wetland plant survival and removal of nutrients from lagoon wastewater in constructed wetlands have been examined by several authors (Breen, 1990; Cronk and Mitsch, 1993; Murphy et al., 1993).

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Surrency (1993) reported on constructed wetland research from four locations in the southeast and concluded that *Scirpus californicus* and *S. validus* (giant cutgrass), *Panicum hemitomon* (maidencane), *Pontedieria cordata* (pickerelweed), *Sagittaria lancifolia* (arrowhead), and *Typha latifolia* (cattail) are the best aquatic plants to use in constructed wetlands for treating wastewater from dairy and swine operations and for municipal constructed wetland systems. In an in−situ containerized field study, Hubbard et al. (1999) evaluated growth and nutrient uptake response of the species *Ilex cassine* (Dahoon holly), *Cephalanthus occidentalis* (buttonbush), *Itea virginica* (Virginia sweetspire), *Spartina patens* (saltmeadow cordgrass), *Juncus effuses* (soft rush), and *Panicum hemitomon* (maidencane) when swine lagoon wastewater was applied. They found that *Cephalanthus* and *Spartina* were best at removing nutrients as compared to the other species.

Additional methods for utilizing and removing the nutrients contained within animal wastewater lagoons are needed. One potential method for removing nutrients would be to have vegetation growing in the lagoon. Vegetation grown directly as floating mats on the lagoon that is then periodically removed would be a mechanism for nutrient removal. Lagoon managers would then have an additional tool for treating or utilizing the nutrients contained in the lagoon wastewater.

Floating islands of vegetation are known to occur naturally. Van Duzer (2001) reported on lush floating vegetative islands found in the sinkholes on El Rancho Azufrosa near the small town of Aldama in the state of Tamaulipas in northeastern Mexico. The water in the sinkholes was highly mineralized, smelling strongly of sulfur, and was also quite warm, with average temperatures ranging from 28.3°C to 33.8°C. The flora of the floating islands was dominated by a grass know as “zacate,” and in fact it is the distinctive islands of zacate that give the sinkhole its name “Zacaton.” The names “zacate” and “zacaton” are applied to several different species, including *Muhlenbergia robusta*, *Festuca amplissima*, and *Sporobolus wrightii*, as well as other species in these genera. A small number of shrubs and cacti also grow on these islands.

Historical reports also exist of floating vegetated islands formed on travertine rafts. A lake now called Lago della Regina, formerly known as Lacus Albuleus, La Solfatra, or Lago delle Isole Natanti, near Tivoli, Italy, once had vegetated floating islands formed on floating masses of travertine. These were famously described by Athanasius Kircher (1671) and Francesco Lana (1684) in the 17th century, and in more detail by Sir Humphry Davy (1830) in the 19th century. Lana (1684) described these floating islands as follows: “I myself saw several of these islands in a small lake of sulfurous water not far from the Tiber; they were mostly circular or oval, and rose four or six inches above the water. Their surface is flat and grassy, and at the edges of some of them a few larger plants grow, which act as sails, so that even the slightest breeze pushes the islands from one part of the lake to another. The largest of them are a few yards in diameter, yet nonetheless can sustain several men standing upon them.”

Little to no research exists evaluating the potential and feasibility of growing vegetative mats in lagoon wastewater for removal of nutrients. It is not known which plant species, if any, will survive in animal wastewater lagoons nor which will produce significant amounts of biomass along with nutrient removal. This study was conducted to investigate the feasibility of using floating mats of vegetation on swine lagoon wastewater, and to measure rates of biomass production and removal of nutrients with the cut vegetation.

Materials and Methods

Field Site and Wastewater Material

The floating mat study was conducted from 2001 to 2002 in tanks (fig. 1) at a field site approximately 760 m from the University of Georgia Coastal Plain Experiment Station main swine research facility at Tifton, Georgia. The swine lagoon wastewater was from the waste treatment−storage system of this facility. This unit had a 120−sow, 5−boar capacity breeding−gestation barn, a 26−place farrowing house, a 320−pig capacity nursery barn, and a grower−finisher barn with a capacity for 240 pigs. The unit maintained a normal inventory of 350 to 550 head of swine during the study. All barns had slatted floors, and waste was flushed from beneath the slats using a combination of lagoon liquid and fresh water. The lagoon system consisted of three lagoons, in series. The primary lagoon (12 × 46 m) discharged into a secondary lagoon (15 × 31 m) from which the liquid was pumped back to the barns (2.2 kW, 1800 L min^{-1}) for flushing of wastes. This secondary lagoon was equipped with a 2.2 kW aerator. The secondary lagoon discharged into a holding lagoon (18 × 37 m), which was used as the source of wastewater for the study. Features of the lagoon system have been described previously (Newton, 1985; Newton and Haydon, 1985). Liquid was pumped from the end of this holding lagoon opposite the infall to the site where the floating mat tests were conducted.

Plant Species, Treatment Design, and Measurements

The study was conducted using floating mats of vegetation in tanks containing different fertility treatments. The floating platforms were built using 0.64 cm diameter PVC pipe, chicken wire, and fibrous matting material. Each frame had an outer square and an inner cross constructed of the PVC pipe. Attached to the sides and supported by the middle T−cross were chicken wire and fibrous matting. Each individual platform was 1 m^2 and was built to float inside of an aquaculture tank capable of holding 1285 L of wastewater.

There were three different nutrient treatments, three different plant species, and four replicates of each combination, for a total of 36 floating mats each contained within an individual tank. The three different nutrient treatments were full−strength wastewater, 1/2−strength wastewater (swine lagoon wastewater mixed with well water), and inorganic nutrients (1/4−strength Hoaglund solution; Hoaglund and Arnon, 1950). The full−strength wastewater contained on average total nutrient concentrations of 160 mg L^{-1} N, 30 mg L^{-1} P, and 45 mg L^{-1} K, while the 1/2−strength wastewater contained half this amount (table 1). Total nutrient concentrations for the 1/4−strength Hoaglund solution were 53 mg L^{-1} N, 8 mg L^{-1} P, and 59 mg L^{-1} K. The 1/4−strength Hoaglund solution was designed to provide sufficient N and P for the plants so that they would not die, but insufficient for rapid growth. The inorganic treatment served as a form of “modified” control for the wastewater treatments. Well water with low concentrations of nutrients could not be used as a

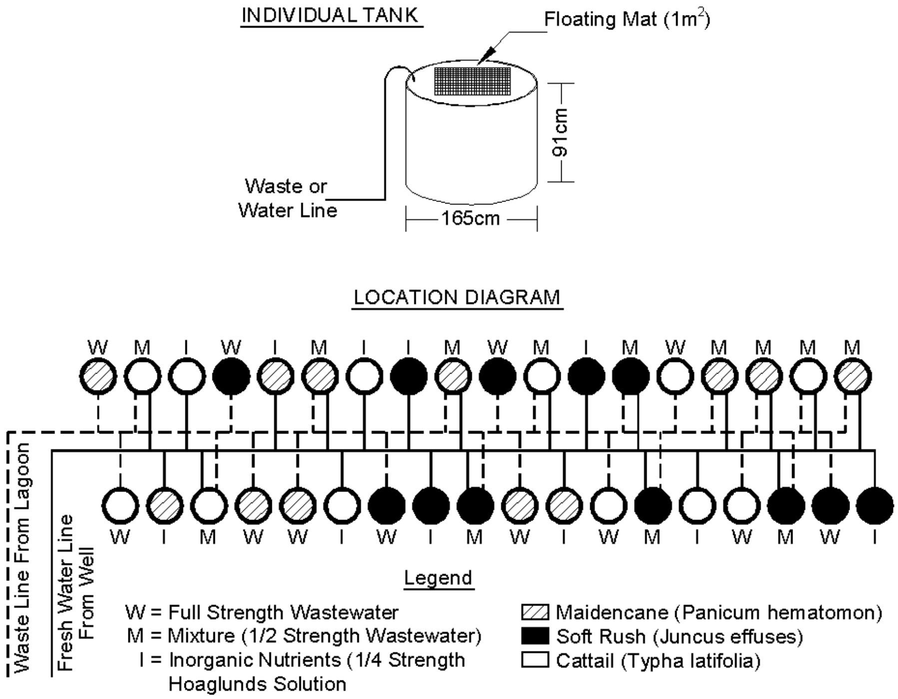

Figure 1. Schematic showing tanks and treatments.

control since the plants most likely would have died. Every two weeks, half of the liquid in each tank was replaced with new liquid of the appropriate nutrient level (full−strength wastewater, 1/2−strength wastewater, or 1/4−strength Hoaglund solution), except during the winter months when the nutrient replacement interval was spread out to every three weeks, since the plants were either dormant or very slow growing. Draining down of the tanks to half the volume and refilling with fresh wastewater, wastewater/well water mixture, or inorganic Hoaglund solution ensured that nutrients were being replaced and made available to the plants. Turbulent mixing of the old and new solutions occurred as the new solution poured from the overhead faucets (wastewater or well water) into the wastewater tank. The wastewater lagoon from which the wastewater was pumped was a retention lagoon that was never drained. Wastewater losses from this lagoon were by evaporation or by pumping of a small volume for this project. The 36 tanks, each containing a separate floating mat, were distributed on the landscape such that the treatments (plant species and type of water) were completely randomized (fig. 1).

Three different wetland plant species were selected for the study: cattail (*Typha latifolia* L.), soft rush (*Juncus effuses*), and maidencane (*Panicum hematomon* Schult ‘Halifax’). The cattail and rush species were selected for the test because of published information concerning their use in constructed wetlands, while the maidencane was selected because we had successfully used it in overland flow vegetated buffer plots receiving swine lagoon wastewater (Hubbard et al., 1998). In addition, all three species were readily available near our research site.

Table 1. Nutrient concentrations in tank solutions (all values in mg L^{-1}).

	Total Nitrogen	Total Phosphorus	Total Potassium
Full−strength lagoon wastewater	160	30	45
1/2−strength lagoon wastewater	80	15	22.5
1/4−strength Hoaglund solution	53	8	59

There is a fairly large body of research on cattail species (*Typha latifolia* L. and *Typha angustifolia* L.) both in natural ecosystems and in constructed wetlands. Considerable research has shown that cattail is adapted to high nutrient availability (Davis, 1991; Newman et al., 1996; Miao and Sklar, 1998; Lorenzen et al., 2001). Newman et al. (1998) found that elevated soil P concentrations were a primary factor influencing cattail growth. In the Everglades, a number of researchers have documented strong relationships between soil P and cattail growth (Richardson et al., 1990; Davis, 1991; Koch and Reddy, 1992; Urban et al., 1993; DeBusk et al., 1994; Rutchey and Vilchek, 1994). Cattail growth has generally been found to be greatest during the spring following winter dormancy (Urban et al., 1993). Coleman et al. (2001), using constructed wetlands, found that cattail species outperformed soft rush species both in growth and in effluent quality improvement. Grime et al. (1988) indicated that soft rush favors damp or wet soils where soil drainage is impeded. Search of the literature did not reveal use of maidencane in constructed wetlands, so little was known prior to this study regarding potential for maidencane to survive and flourish as a floating matt. Both cattail and maidencane become dormant during the winter months, while soft rush remains green.

The maidencane was obtained from research plots on vegetated buffer systems (Hubbard et al., 1998) located at the same field site where the floating mat study was conducted. The cattail and rush were dug from the edges of two different ponds on the University of Georgia Animal and Dairy Science Farm at Tifton, Georgia. The plant materials were placed on the mats either the same day as they were dug or the following day. For the cattail and rush, 20 sprigs of plant material (five per corner section) were placed on top of each floating mat, respectively. For the maidencane, which was a

Table 2. Mean monthly air temperatures during the study (°C).

	2001	2002	Mean Annual
January	−−	11.3	9.9
February	−−	10.6	11.0
March	−−	16.1	14.3
April	−−	21.6	19.1
May	−−	22.9	23.1
June	25.5	26.2	26.0
July	26.9	27.9	26.9
August	26.7	27.2	26.9
September	23.4	26.2	24.7
October	18.1	−−	19.7
November	17.6	−−	14.2
December	13.3	−−	10.3

smaller plant than the cattail or rush, we placed 40 plants on each floating mat (ten per corner section).

The study started in June 2001 with sprigging of plant material on each floating mat. The plant biomass on each floating mat was then periodically harvested from August 2001 through September 2002. The plants were cut so as to leave about 5 cm of green material above the base of each floating platform for regrowth. The cattail and maidencane were harvested on 20 Aug. 2001, 15 Oct. 2001, 3 June 2002, 29 July 2002, and 30 Sept. 2002. The rush was harvested on the same dates with an additional harvest on 14 March 2002. The additional harvest for the rush was because it continued to grow during the winter months of 2001−2002 while the other two species went dormant.

Measurements of total biomass, leaf area, and percent N, P, and K in the plant tissue were made at each plant harvest. Biomass measurements were made on oven−dried (55°C) material. Leaf area measurements of the entire harvested biomass were made using a stationary (laboratory) Li−Cor leaf area meter (model Li−3000A) with a Li−Cor transparent belt conveyor accessory automated belt feed (model Li−3050 A/4). Nutrient analyses (percent N, P, and K) were made of the tissue samples from each cutting. Nitrogen analyses were performed on a Leco NCS 2000. Analyses for P were by spectrophotometer (Milton Roy 501 Spectronic), while analyses for K were by atomic absorption. Statistical comparisons were made of biomass yield, leaf area, and nutrient content in the plant tissue by nutrient source and plant species using the T−test least−significant difference (LSD) procedure of general linear models (GLM) at the 0.05 level of significance (SAS, 2003). Since plant growth is affected by climate, the mean monthly air temperatures during the study along with mean annual monthly air temperatures at Tifton, Georgia (31° 44′ N 83° 46′ W) are shown in table 2.

RESULTS

BIOMASS

Mean biomass per cutting for the cattail ranged from a low of 106 g m^{-2} for the wastewater treatment on 30 Sept. 2002 to a high of 5794 g m^{-2} on 3 June 2002 (table 3). Although there were some statistically significant differences in cattail biomasses between treatments for individual cutting dates, there were no significant differences in the overall totals. There were differences in cattail biomass between cutting dates that primarily related to the length of time that the plants grew between cuttings. Initially, there was rapid growth of the cattail between sprigging in June 2001 and the cutting of 20 Aug. 2001, particularly for the plants grown on the mixture and on the full−strength wastewater. There was also considerable growth between the fall cutting of 15 Oct. 2001 and the first 2002 cutting on 3 June 2002. This was the rapid spring growth following winter dormancy, which is characteristic of cattail (Richardson et al., 1990; Newman et al., 1996; Newman et al., 1998).

Mean biomass per cutting for the rush ranged from a low of 78 g m^{-2} for the wastewater treatment on 15 Oct. 2001 to a high of 2493 g m^{-2} for the inorganic treatment on 3 June 2002. As with the cattail, there were no significant overall differences in biomass due to treatment, although one cutting of the rush (14 March 2002) did have significant treatment effects. No biomass data is shown for the rush on 29 July 2002 or 30 Sept. 2002 for the mixture or full−strength wastewater treatments. This is because the rush growing on these mats did not survive. In addition, the rush on the inorganic nutrient solution grew rather poorly. Grime et al. (1988) indicated that rush grows naturally in poorly drained soils, as opposed to fully saturated conditions. Although not measured, low oxygen levels in the wastewater may explain why the rush died. Clearly, the rush species is not suitable for growth as floating vegetation in wastewater.

Mean biomass per cutting for the maidencane varied from 453 g m^{-2} for the inorganic treatment on 15 Oct. 2001 to 5903 g m^{-2} for the mixture on 3 June 2002. Although not always significantly different from the other treatments, the mean biomass for the maidencane grown on the mixture was numerically greater than that of the other treatments for all sampling dates. The total mean biomass removed by the maidencane grown on the mixture was significantly greater

Table 3. Mean biomass (all values in g m^{-2}).[a]

	Cattail						Rush						Maidencane					
	Inorganic		Mixture		Waste		Inorganic		Mixture		Waste		Inorganic		Mixture		Waste	
Date	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
20 Aug. 01	1753^{cd}	809	4443^{a}	1441	5223^{a}	1489	715de	141	834de	135	183^{e}	136	689^{e}	391	3301^{b}	431	2343^{bc}	640
15 Oct. 01	1599^{bcd}	1452	3911^{a}	1800	2875^{ab}	1387	275^{e}	90	811^{cde}	381	78^{e}	47	453de	311	1760^{bc}	381	1607^{bcd}	294
14 Mar. 02	−−	−−	−−	−−	−−	−−	1523^{ab}	977	2264^{a}	2414	266^{bc}	204	−−	−−	−−	−−	−−	−−
3 June 02	4544^{ab}	4576	2500^{abc}	2710	5794^{a}	2073	2493^{abc}	1677	1759^{bc}	1408	81^{c}	115	4061^{ab}	2854	5903^{a}	674	2830^{abc}	1459
29 July 02	2543^{ab}	2699	931^{bc}	1096	2513^{ab}	1479	183^{c}	121	−−	−−	−−	−−	2559^{ab}	1721	3768^{a}	778	1421^{bc}	486
30 Sept. 02	599^{bcd}	793	186^{cd}	222	106^{d}	136	270^{cd}	351	−−	−−	−−	−−	1136^{bc}	632	3188^{a}	1707	1550^{b}	857
Totals	11038^{abc}		11971^{abc}		16511^{ab}		5459^{cd}		5668^{cd}		608^{d}		8898^{c}		17920^{a}		9751^{bc}	

[a] Letters denote T−tests least−significant difference (LSD) in the same row. Where letters are the same, means are not significantly different at the 0.05 level.

Table 4. Mean leaf area (all values in cm²).[a]

	Cattail						Rush						Maidencane					
	Inorganic		Mixture		Waste		Inorganic		Mixture		Waste		Inorganic		Mixture		Waste	
Date	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
20 Aug. 01	27414[d]	13429	81019[a]	12744	88376[a]	15075	11293[e]	2474	11066[e]	714	2681[e]	2112	10725[e]	7879	60856[b]	8521	46013[c]	13895
15 Oct. 01	32397[cde]	28991	98272[a]	42967	69529[ab]	32783	4775[ef]	1562	17522[def]	10815	1394[f]	882	14738[def]	9929	58654[bc]	9490	43731[bcd]	16801
14 Mar. 02	−−	−−	−−	−−	−−	−−	29637[a]	16644	41218[a]	36215	5297[b]	4241	−−	−−	−−	−−	−−	−−
3 June 02	77519[ab]	73579	52114[bc]	54952	104736[ab]	45928	41115[bc]	37741	33976[bc]	25498	996[c]	1756	79529[ab]	57835	126049[a]	19602	63524[abc]	25554
29 July 02	47496[bc]	45566	16513[d]	20296	46256[bc]	25615	3468[d]	2463	−−	−−	−−	−−	54497[b]	38730	93224[a]	21744	27563[bcd]	10509
30 Sept. 02	15078[bc]	21294	3419[c]	4403	1455[c]	1979	4308[c]	7235	−−	−−	−−	−−	22800[bc]	15633	84284[a]	38386	36617[b]	23501
Totals	199904[bcd]		251337[bc]		310352[ab]		94596[de]		103782[de]		10368[e]		182289[cd]		423067[a]		217448[bcd]	

[a] Letters denote T−tests least−significant difference (LSD) in the same row. Where letters are the same, means are not significantly different at the 0.05 level.

than that of the other two treatments. These results indicate that the mixture gave the maidencane an optimal nutrient level for growth, while the full−strength wastewater suppressed growth back to the same level as the maintenance level of nutrients for the inorganic treatment. Overall, the biomass results showed that both the cattail and maidencane were suitable species for growing on floating mats on lagoon wastewater at the wastewater strength used for this study, but that the rush was unsuitable for growth in wastewater or on floating mats.

Leaf Area

Leaf area measurements reflected both the natural size and shape of the plant species and their response to the three different fertility treatments (table 4). For the individual samplings, the mean leaf area of the cattail ranged from a low of 1455 cm^2 for the wastewater treatment on 30 Sept. 2002 to a high of 104,736 cm^2 for the wastewater treatment on 3 June 2002. At the first two cutting dates, cattail grown on the mixture and wastewater treatments had significantly greater mean leaf areas than cattail grown on the inorganic treatment, but this treatment difference disappeared later in the study. Total mean leaf area summed from all of the cattail cuttings showed no significant differences between nutrient treatments, although the mean leaf areas from the wastewater and mixture treatments were both numerically greater than that from the inorganic treatment.

For the rush, the main trend was the decline and death of the plants grown with the mixture and the full−strength wastewater. For the maidencane, the mean leaf area was significantly greater with the mixture than with the inorganic or full−strength wastewater on three different cutting dates (20 Aug. 2001, 29 July 2002, and 30 Sept. 2002), and the total mean leaf area was greatest at the mixture nutrient strength. This difference between the mixture and the other two treatments was statistically significant.

Comparison of the mean leaf areas among the three plant species showed that both the maidencane and the cattail produced significant amounts of biomass on the floating mats, regardless of nutrient source.

Nutrient Content of Tissue

The mean percentages of N, P, and K in the plant tissue are shown both for the background sampling of 19 June 2001 and the cuttings made during the study (tables 5, 6, and 7). For N, the background mean contents were all less than 2% (table 4). Once the plants began growing on the floating mats and an N source was available, the mean percentages of N in the tissue all jumped to greater than 2% for the remainder of the study, except for the cuttings of the cattail and maidencane from the inorganic treatment on 30 Sept. 2002. For many of the cuttings of both the cattail and maidencane, the mean N content of the tissue was significantly greater with full−strength wastewater than with the inorganic N source. No significant differences were observed in mean N content of the rush for any of the cuttings.

Mean P percentages in all three species for all cuttings were less than 1% (table 6). As compared to the background sampling of 19 June 2001, more P was in the tissue for all three nutrient treatments after the plants were moved to the floating mats and water containing a P source. For the cattail, the initial mean P contents of the tissue ranged from 0.19% to 0.24%, while thereafter the P contents ranged from 0.39% to 0.58%. There were no significant differences in mean P content of the cattail tissue among any of the three nutrient treatments except for the cutting of 29 July 2002, when the P content of the plants from the mixture treatment was significantly greater than that of the plants from the inorganic treatment.

For the rush, the initial P content ranged from 0.07% to 0.12%. Once P was supplied from either the inorganic nutrient solution or the wastewater, the P contents of the rush

Table 5. Mean N in tissue (all values in %).[a]

	Cattail						Rush						Maidencane					
	Inorganic		Mixture		Waste		Inorganic		Mixture		Waste		Inorganic		Mixture		Waste	
Date	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
19 June 01	1.75[a]	0.14	1.92[a]	0.04	1.31[b]	0.45	1.03[c]	0.08	0.97[c]	0.15	1.17[bc]	0.12	1.34[b]	0.10	1.36[b]	0.19	1.35[b]	0.10
20 Aug. 01	3.41[ab]	0.04	3.51[a]	0.17	3.24[ab]	0.10	2.21[e]	0.07	2.34[de]	0.22	2.72[cd]	0.26	3.57[a]	0.44	3.05[bc]	0.19	3.25[ab]	0.64
15 Oct. 01	2.83[ef]	0.21	2.92[de]	0.19	3.44[b]	0.21	2.64[f]	0.11	3.00[cde]	0.07	3.16[c]	0.09	3.07[cd]	0.18	3.13[cd]	0.11	3.69[a]	0.24
14 Mar. 02	−−	−−	−−	−−	−−	−−	3.06[a]	0.19	2.88[a]	0.28	3.22[a]	0.22	−−	−−	−−	−−	−−	−−
3 June 02	2.43[c]	0.19	2.80[bc]	0.33	3.04[ab]	0.04	2.22[c]	0.90	2.52[bc]	0.24	2.25[c]	0.06	2.22[c]	0.27	2.67[bc]	0.11	3.50[a]	0.17
29 July 02	2.35[cd]	0.16	3.10[ab]	0.55	3.45[a]	0.19	2.30[d]	0.11	−−	−−	−−	−−	2.15[d]	0.17	2.72[bc]	0.29	3.37[a]	0.36
30 Sept. 02	1.71[c]	0.06	2.85[ab]	−−	3.34[a]	0.33	2.00[bc]	0.24	−−	−−	−−	−−	1.70[c]	0.60	2.79[ab]	0.82	3.08[a]	0.23

[a] Letters denote T−tests least−significant difference (LSD) in the same row. Where letters are the same, means are not significantly different at the 0.05 level.

Table 6. Mean P in tissue (all values in %).[a]

	Cattail						Rush						Maidencane					
	Inorganic		Mixture		Waste		Inorganic		Mixture		Waste		Inorganic		Mixture		Waste	
Date	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
19 June 01	0.19^{b}	0.07	0.24^{ab}	0.03	0.20^{b}	0.06	0.10^{c}	0.03	0.12^{c}	0.05	0.07^{c}	0.05	0.25^{ab}	0.02	0.28^{a}	0.01	0.30^{a}	0.01
20 Aug. 01	0.53^{a}	0.02	0.54^{a}	0.01	0.54^{a}	0.02	0.35^{c}	0.03	0.39^{bc}	0.02	0.40^{b}	0.02	0.35^{c}	0.08	0.55^{a}	0.03	0.52^{a}	0.03
15 Oct. 01	0.46^{cd}	0.06	0.50^{bc}	0.01	0.50^{bc}	0.02	0.37^{e}	0.03	0.46^{cd}	0.03	0.45^{cd}	0.02	0.40^{de}	0.10	0.58^{a}	0.01	0.53^{ab}	0.01
14 Mar. 02	−−	−−	−−	−−	−−	−−	0.34^{a}	0.02	0.37^{a}	0.05	0.35^{a}	0.01	−−	−−	−−	−−	−−	−−
3 June 02	0.39^{bc}	0.01	0.41^{b}	0.03	0.39^{bc}	0.01	0.33^{cd}	0.02	0.37^{bc}	0.03	0.51^{a}	0.03	0.29^{d}	0.07	0.38^{bc}	0.05	0.50^{a}	0.09
29 July 02	0.49^{b}	0.10	0.58^{a}	0.04	0.53^{ab}	0.03	0.34^{c}	0.02	−−	−−	−−	−−	0.22^{d}	0.05	0.36^{c}	0.03	0.40^{c}	0.03
30 Sept. 02	0.40^{bcd}	0.04	0.49^{abc}	−−	0.50^{ab}	0.02	0.36^{de}	0.01	−−	−−	−−	−−	0.27^{e}	0.07	0.38^{cde}	0.02	0.54^{a}	0.10

[a] Letters denote T−tests least−significant difference (LSD) in the same row. Where letters are the same, means are not significantly different at the 0.05 level.

tissue ranged from 0.33% to 0.51%. Since the rush ultimately died, except for the inorganic treatments, the P content of the rush tissue is not really of concern, since this species is not suitable for floating mats in wastewater lagoons.

The initial mean P content of the maidencane ranged from 0.25% to 0.30%. After supplying P with inorganic solution or wastewater, the mean P contents of the maidencane ranged from 0.22% to 0.55%. The mean P contents of the maidencane were significantly greater for the wastewater and mixture treatments than for the inorganic treatment for most of the sampling dates. Overall, there was little difference between the mean P contents of the maidencane and cattail.

The mean K contents of the cattail and rush tissue at the background sampling in June 2001 were less than 2%, while the background K in the maidencane tissue was just slightly over 2% (table 7). Once the plants were moved onto floating mats with K in solution, the K contents of all three plant species increased. For the cattail, K contents all increased to in excess of 2.8%, with most of the values in the 3% to 4% range. There were no significant differences in K content of the cattail during 2001, but in 2002 all cuttings of cattail showed the significantly different pattern of mixture > wastewater > inorganic.

The rush showed an increase in K content from the background range of 0.97% to 1.45%, to the new range of 1.33% to 2.67%. The K contents of the maidencane also increased as compared to the background levels, but there was little significant difference between the different nutrient levels.

Total Nitrogen Removal

Mean total N removal with cattail biomass by sampling date ranged from a low of 7.3 g m^{-2} with wastewater on 30 Sept. 2002 to a high of 176.4 g m^{-2} on 3 June 2002, also with wastewater (table 8). The mean total N removal by sampling date for the cattail varied among the inorganic, mixture, and full−strength wastewater, with no consistent

Table 7. Mean K in tissue (all values in %).[a]

	Cattail						Rush						Maidencane					
	Inorganic		Mixture		Waste		Inorganic		Mixture		Waste		Inorganic		Mixture		Waste	
Date	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
19 June 01	1.47^{bc}	0.75	1.84^{ab}	0.33	1.91^{ab}	0.26	0.97^{c}	0.23	1.45^{bc}	0.22	1.10^{c}	0.22	1.71^{ab}	0.37	2.19^{a}	0.17	2.10^{a}	0.35
20 Aug. 01	3.82^{a}	0.21	3.70a	0.97	3.78^{a}	0.45	1.95^{bc}	0.36	1.33^{c}	0.19	1.47^{c}	0.23	2.36^{b}	0.64	2.37^{b}	0.47	2.35^{b}	0.64
15 Oct. 01	3.73^{a}	0.49	3.99^{a}	0.51	3.65^{a}	0.11	2.67^{c}	0.15	2.93^{b}	0.13	2.30^{c}	0.19	2.86^{b}	0.02	2.64^{b}	0.29	2.30^{c}	0.36
14 Mar. 02	−−	−−	−−	−−	−−	−−	2.57^{a}	0.23	2.56^{a}	0.27	2.21^{a}	0.00	−−	−−	−−	−−	−−	−−
3 June 02	3.62^{b}	0.24	4.48^{a}	0.42	2.76^{c}	0.31	2.19^{d}	0.19	1.85^{de}	0.31	1.79^{e}	0.23	2.57^{c}	0.20	1.66^{e}	0.11	2.02^{de}	0.22
29 July 02	4.75^{b}	1.32	5.97^{a}	0.53	3.47^{c}	0.21	2.26^{d}	0.08	−−	−−	−−	−−	2.30^{d}	0.15	2.05^{d}	0.16	2.53^{d}	0.09
30 Sept. 02	3.38^{c}	0.29	6.21^{a}	−−	4.55^{b}	1.54	2.35^{d}	0.20	−−	−−	−−	−−	2.22^{d}	0.31	1.98^{d}	0.13	2.36^{d}	0.08

[a] Letters denote T−tests least−significant difference (LSD) in the same row. Where letters are the same, means are not significantly different at the 0.05 level.

Table 8. Mean total N removed (all values in g m^{-2}).[a]

	Cattail						Rush						Maidencane					
	Inorganic		Mixture		Waste		Inorganic		Mixture		Waste		Inorganic		Mixture		Waste	
Date	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
20 Aug. 01	59.6^{c}	26.9	155.8^{a}	51.1	168.7^{a}	44.7	15.8^{d}	3.4	19.6^{d}	4.0	4.8^{d}	3.0	25.3^{d}	14.7	100.6^{b}	13.9	73.2^{bc}	46.4
15 Oct. 01	46.4^{cd}	41.8	112.5^{a}	48.5	97.3^{ab}	43.2	7.3^{e}	2.4	24.2^{cde}	11.0	2.5^{e}	1.5	18.7^{de}	3.8	55.0^{cd}	12.3	59.2^{bc}	11.0
14 Mar. 02	−−	−−	−−	−−	−−	−−	46.2^{a}	29.1	60.9^{a}	59.4	11.4^{a}	3.9	−−	−−	−−	−−	−−	−−
3 June 02	144.1^{abc}	92.3	65.0^{cde}	67.9	176.4^{a}	64.8	49.7^{de}	23.8	46.5^{de}	41.5	3.6^{e}	2.5	85.4^{bcde}	60.7	157.7^{ab}	23.7	97.4^{abcd}	46.1
29 July 02	79.1^{ab}	57.4	36.0^{bc}	27.6	84.8^{ab}	48.5	4.1^{c}	2.7	−−	−−	−−	−−	53.3^{abc}	35.4	102.2^{a}	22.8	46.6^{abc}	13.1
30 Sept. 02	20.3^{bc}	10.8	8.6^{c}	−−	7.3^{c}	4.1	4.9^{c}	5.9	−−	−−	−−	−−	16.9^{bc}	7.7	79.2^{a}	25.6	46.3^{ab}	24.3
Totals	349.5^{cd}		377.9^{bc}		534.5^{a}		128.0^{ef}		151.2^{ef}		22.3^{f}		199.6^{de}		494.7^{ab}		322.7^{cd}	

[a] Letters denote T−tests least−significant difference (LSD) in the same row. Where letters are the same, means are not significantly different at the 0.05 level.

Table 9. Mean total P removed (all values in g m^{-2}).[a]

	Cattail						Rush						Maidencane					
	Inorganic		Mixture		Waste		Inorganic		Mixture		Waste		Inorganic		Mixture		Waste	
Date	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
20 Aug. 01	9.3^{c}	4.4	24.1^{a}	7.8	28.3^{a}	8.8	2.5^{d}	0.7	3.3^{d}	0.5	0.7^{d}	0.5	2.6^{d}	1.7	18.2^{b}	2.0	12.3^{bc}	3.6
15 Oct. 01	7.7^{bcde}	6.9	19.8^{a}	9.6	14.3^{ab}	6.8	1.0^{ef}	0.4	3.7^{cdef}	1.4	0.3^{f}	0.2	2.5^{def}	0.8	10.1^{bc}	2.1	8.5^{bcd}	1.5
14 Mar. 02	−−	−−	−−	−−	−−	−−	5.3^{a}	3.8	8.3^{a}	8.3	1.3^{a}	0.5	−−	−−	−−	−−	−−	−−
3 June 02	23.4^{a}	16.4	9.7^{abc}	10.2	22.5^{ab}	8.7	8.4^{bc}	6.1	6.3^{c}	4.5	0.9^{c}	0.6	13.0^{abc}	9.7	22.3^{ab}	2.8	13.3^{abc}	6.3
29 July 02	16.5^{a}	11.5	6.9^{bc}	5.6	12.9^{ab}	7.1	0.6^{c}	0.4	−−	−−	−−	−−	6.3^{bc}	4.4	13.6^{ab}	2.9	5.7^{bc}	2.0
30 Sept. 02	4.9^{ab}	3.2	1.5^{b}	−−	1.1^{b}	0.5	1.0^{b}	1.2	−−	−−	−−	−−	2.7^{b}	1.4	11.8^{a}	6.1	7.8^{ab}	3.6
Totals	61.8^{abc}		62.0^{abc}		79.1^{a}		18.8^{f}		21.6^{ef}		3.2^{f}		27.1^{def}		76.0^{ab}		47.6^{cde}	

[a] Letters denote T−tests least−significant difference (LSD) in the same row. Where letters are the same, means are not significantly different at the 0.05 level.

pattern as to which nutrient treatment had the greatest N removal. Mean total N removal for the record period was significantly greater for the full−strength wastewater than for the mixture and inorganic treatments. This indicated that the cattail was well tolerant of the wastewater strength used for the study and was effective at removing N.

The mean total N uptake by the rush was lower than that of either the cattail or maidencane. As discussed earlier, the rush grown on the mixture and full−strength wastewater had died by the cutting of 29 July 2002. It appears that the rush growing on the mixture was initially outperforming the rush grown on the inorganic solution and on the full−strength wastewater. Ultimately however, even the rush grown on the mixture was growing poorly. Rush species normally grow on the sides of ponds, although they have been grown successfully in standing water in constructed wetlands (Coleman et al., 2001). Grime et al. (1988) indicated that rush favors damp or wet soils where soil drainage is impeded. The literature does not report rush as growing under very low oxygen conditions. Most likely, rush is very sensitive to oxygen levels, and the failure of the rush to survive in our study was due to insufficient oxygen as opposed to excess nutrients. However, the important conclusion regarding rush is that for the wastewaters tested, and by inference for other wastewater lagoons, this species will not do well in a completely hydroponic situation.

Mean total N removal per cutting by the maidencane ranged from a low of 16.9 g m^{-2} for the inorganic treatment on 30 Sept. 2002 to a high of 157.7 g m^{-2} for the plants grown on the mixture on 3 June 2002. Numerically, the mean total N removal by the maidencane grown on the mixture was generally greater than that of the other two treatments. This trend also appeared in the mean total N removal by all cuttings of the maidencane grown on the mixture, which was significantly greater than removal by the maidencane on the inorganic or wastewater treatments.

Total Phosphorus Removal

Mean total P removal by the cattail ranged from a low of 1.1 g m^{-2} for the wastewater treatment on 30 Sept. 2002 to a high of 28.3 g m^{-2} for the wastewater treatment on 20 Aug. 2001 (table 9). Although there were significant treatment differences in mean total P removed on the cuttings of 15 Oct. 2001 and 29 July 2002, there was no trend in the pattern of differences. Overall, there were no significant differences among treatments in mean total P removal by cattail for the entire study period.

The rush species receiving the mixture or full−strength wastewater removed P up until sickness or death of the plants. Removal was always numerically least for the full−strength wastewater, although the differences among treatments were not significant. Since the rush grew badly or did not survive on the floating mats, the total P removed during the cutting period was less than that of either the maidencane or cattail.

Mean total P removal by the maidencane was greatest with the mixture. There was a significant difference between mean total P removed by the maidencane grown on the mixture and that grown on the inorganic solution for some but not all of the dates. Mean total P removed over the entire study period was significantly greater from plants grown on the mixture than that removed by either the wastewater or inorganic treatments. The greatest removal of P by plants growing on full−strength wastewater was by the cattail.

Total Potassium Removal

Mean total K removed by the cattail ranged from a low of 10.4 g m^{-2} on 30 Sept. 2002 for the wastewater treatment to 213.5 g m^{-2} for the inorganic treatment on 3 June 2002 (table 10). There were no statistically significant differences between treatments for the cattail cuttings on specific dates except for the cutting of 20 Aug. 2001, when the plants grown on the inorganic treatment had significantly less removal of K than the other two treatments, and the cutting of 15 Oct. 2001, when the inorganic treatment had significantly less K removal than the plants grown on the mixture. The total removal of K by the cattail was significantly greater than that removed by the rush and the maidencane except for the mixture treatment of the maidencane.

Mean total removal of K per cutting by the rush was much lower than that removed by the cattail and maidencane. Mean total K removal overall by the rush was quite low, since the rush died or grew very poorly. Mean total K removal by the maidencane was generally greatest for the mixture, except for the cutting of 3 June 2002, when the mean total K removal was greatest for the inorganic treatment. The maidencane clearly grew best and removed the most K at the 1/2−strength wastewater nutrient level. Overall, the cattail removed the greatest K from full−strength wastewater.

Mass Balance Calculations

Mass balance calculations were made of the total percent nutrient removal by the floating mats (table 11). For these calculations, it was assumed that the root zone depth was 15 cm for both the rush and maidencane, and that it was 30 cm for the cattail. It was also assumed that the total available nutrients to the plants was the sum of the nutrients contained in the 26 applications of the solutions for the total wastewater volume corresponding to the thickness of this

Table 10. Mean total K removed (all values in g m^{-2}).[a]

	Cattail						Rush						Maidencane					
	Inorganic		Mixture		Waste		Inorganic		Mixture		Waste		Inorganic		Mixture		Waste	
Date	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
20 Aug. 01	66.9^{bc}	31.0	173.2^{a}	82.3	201.3^{a}	74.0	13.8^{cd}	2.8	11.2^{d}	3.4	2.9^{d}	2.8	18.0^{cd}	13.7	78.1^{b}	17.5	56.2^{bcd}	26.5
15 Oct. 01	60.0^{bc}	52.4	160.4^{a}	87.3	105.6^{ab}	53.2	6.3^{cd}	2.4	24.0^{cd}	12.1	1.8^{d}	1.0	17.2^{cd}	2.5	45.6^{cd}	5.1	37.6^{cd}	10.8
14 Mar. 02	−−	−−	−−	−−	−−	−−	39.4^{a}	26.5	62.9^{a}	73.8	7.8^{a}	2.7	−−	−−	−−	−−	−−	−−
3 June 02	213.5^{a}	141.8	109.6^{abc}	111.0	158.3^{ab}	50.6	56.6^{bc}	43.9	35.4^{bc}	31.0	2.8^{c}	1.7	105.9^{abc}	78.3	98.5^{abc}	17.1	56.5^{bc}	30.6
29 July 02	158.2^{a}	107.5	76.3^{ab}	72.1	86.9^{ab}	52.3	4.2^{b}	2.8	−−	−−	−−	−−	56.8^{b}	38.1	77.9^{ab}	20.3	36.1^{b}	13.1
30 Sept. 02	41.4^{ab}	26.2	18.8^{ab}	−−	10.4^{b}	7.8	6.7^{b}	9.2	−−	−−	−−	−−	24.3^{ab}	13.6	62.9^{a}	33.1	36.4^{ab}	20.1
Totals	540.0^{a}		538.3^{a}		562.5^{a}		127.0^{cd}		133.5^{cd}		15.3^{d}		222.2^{bcd}		363.0^{abc}		222.8^{bcd}	

[a] Letters denote T−tests least−significant difference (LSD) in the same row. Where letters are the same, means are not significantly different at the 0.05 level.

root zone. In reality, this is not quite true, since nutrients in solution below the assumed root zone thickness could freely mix with the solution in the root zone. Hence, where the mass balance calculations (table 11) show percentages greater than 100, natural mixing of the solutions within the tanks clearly provided nutrients in excess of those calculated using our root zone thickness assumptions.

Mass balance calculations for N removal ranged from a low of 4% for the rush grown on wastewater to a high of 157% for the maidencane grown on the mixture. For both the cattail and rush, the percent N removal decreased in the order inorganic > mixture > wastewater. This showed that for the mixture and wastewater treatments, N was in excess of plant needs. The rush died with both the mixture and full−strength wastewater, which is why the N removal percentages for these two treatments are low. The maidencane showed in excess of 100% N removal from the mixture, indicating that N was removed from deeper in the tank than the assumed root zone thickness. In addition, a thinner root zone thickness was assumed for the maidencane than for the cattail, which may contribute some to the calculated higher percent N removal by the maidencane than by the cattail.

For P, the percent removal ranged from 3% for the rush grown on wastewater to 130% for the maidencane grown on the mixture. Nutrient removal is the product of nutrient content of the tissue and biomass removed, but the dominating factor with P, as with N, was the amount of biomass produced. For both N and P, the inorganic treatment root zone clearly just met nutrient needs, while for both the mixture and full−strength wastewater, excess nutrients were available.

For K, mass balance calculations showed a different pattern than that observed for N and P. Both the cattail and maidencane removed as much or more K than that contained in the root zone thickness. The inorganic treatment had more K than the wastewater and mixture; however, these two species still used all of the K from the inorganic treatment. The rush only removed 55% of the K from the inorganic treatment and died in the other two treatments, so K removal percentages are really unimportant since this species is not suitable for use on floating mats.

Overall, the mass balance calculations showed that we were meeting the nutrient needs for the cattail and maidencane with the inorganic treatment, had an excess of N and P with the full−strength wastewater, and that with greater growth on 1/2−strength wastewater, the maidencane utilized N in excess of that from the assumed root zone thickness. For both the cattail and rush, more K was removed than was available from the assumed root zone thickness. Clearly, a wastewater lagoon with continuous inputs of fresh animal waste and floating mats will in most cases provide nutrient amounts such that the plants on the mats are in a luxury uptake situation, and removal of nutrients from the lagoons will be a function of biomass produced and the maximum plant nutrient uptake levels.

Conclusions

Overall, this study showed that floating mats of vegetation can be grown in wastewater lagoons, and that the cattail was the best plant species for biomass production and nutrient removal. At the wastewater strength used for this study, both the maidencane and cattail survived and removed nutrients. The rush, although initially showing promise, ultimately died and also showed growth problems with the inorganic control treatment. Hence the rush is unsuitable for growth on floating mats. Total biomass produced on full−strength wastewater during the study was 16,511 g m^{-2} and 9751 g m^{-2} for the cattail and maidencane, respectively. Total N, P, and K removed on full−strength wastewater were 534, 79, and 562 g m^{-2} for the cattail and 323, 48, and 223 g m^{-2} for the maidencane. Using an assumed root zone thickness of 30 cm for cattail and 15 cm for maidencane, mass balance calculations showed that, on full−strength wastewater, the cattail removed 43%, 34%, and 160% of the applied N, P, and

Table 11. Calculated percent nutrient removed from the root zone by the floating mats (all values in %).[a]

	Nitrogen			Phosphorus			Potassium		
	Inorganic	Mixture	Wastewater	Inorganic	Mixture	Wastewater	Inorganic	Mixture	Wastewater
Cattail	84	61	43	99	53	34	117	307	160
Rush	62	48	4	60	37	3	55	154	9
Maidencane	97	157	52	87	130	41	97	413	127

[a] Calculations of percent nutrient removal were made assuming rooting zone depths of 15 cm for the rush and maidencane and 30 cm for the cattail. It was also assumed that the total available nutrients was the sum of 26 applications of the solution for the thickness of this root zone. Where calculations result in percentages greater than 100, natural mixing of the nutrients within the tank would have provided nutrients in addition to those calculated just for the root zone thickness.

K, respectively, while the maidencane removed 52%, 41%, and 127%. More K was needed than that calculated as being supplied by the wastewater in the root zone. This K clearly came from mixing of wastewater within the tank. The mass balance calculations showed that N and P were in excess of plant needs for the full−strength wastewater for the assumed root zone thickness. Since root zone thicknesses used for the mass balance calculations were 15 or 30 cm, and lagoons are commonly in excess of 2 m deep, in most cases, lagoon nutrients will be greatly in excess of potential plant uptake and removal. This research showed that vegetation can be successfully grown as floating mats in wastewater lagoons with periodic biomass removal, and that this technique can be a tool for animal producers for removing a portion of the nutrients from their wastewater lagoons.

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