American Journal of Agricultural and Biological Sciences 2 (3): 206-217, 2007
ISSN 1557-4989

A Hydroponic System for Purification of Anaerobically Treated Dairy Manure and Production of Wheat as a Nutritional Forage Crop

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Abstract: A hydroponic system was developed and used for purification of an anaerobically treated dairy manure and production of forage crops. The effect of light duration, seeding rate and wastewater application rate on the crop yield and pollution potential reduction were studied. The results indicated that a wheat forage crop can be produced in 21 days from germination to harvest in this system and removal efficiencies of up to 89.9, 94.6, and 86.7 % can be achieved for the total solids, chemical oxygen demand (COD) and ammonium nitrogen, respectively. Increasing the wastewater application rate increased the crop yield and decreased the pollutants removal efficiencies. A treatment combination of wastewater application rate of 900 mL/day, a seeding rate of 400 g and a light duration of 12 hours gave the best results for crop yield (3.65 kg of wheat/tray). A total possible yield of 3160 tonnes per hectare per year can be achieved with the system (with thirteen harvests per year). This is more than 98 times greater than the yield obtainable from a field grown conventional forage of 245 tonnes per hectare per year. At the optimum forage production, removal efficiencies of 75.7, 85.9 and 75.6% were achieved for the solids, COD, ammonium nitrogen, respectively. A nitrate nitrogen concentration of 6.7 mg/L was found in the effluent from the hydroponic system. This is below the Canadian Environmental and Health Guidelines of 10 mg/L.

Key words: hydroponic, purification, light, wastewater application, seeding rate, COD, nitrogen, solids, forage

INTRODUCTION

Manure produced from dairy farms contains residues of feed and bedding in addition to urine and feces from animals. Animal manure exerts an adverse environmental impact when it finds its way to surface and ground water. Organic and inorganic compounds reduce dissolved oxygen levels resulting in the destruction of aquatic life. Solids contribute to building up of bottom sediments and high nutrients loading impairs the quality of water by stimulating excessive phytoplankton production. Animal wastes can, also, be a source of numerous human and livestock diseases as well as odor and other nuisances all of which call for proper treatments before utilization or disposal[1].

Anaerobic digestion of animal manure with energy recovery through methane productions is an effective means of solving the manure pollution problem, while producing gas which could be used for space and water heating of farm houses and animal shelters, grain drying and as a fuel for heating greenhouses during the cold winter[2-4]. However, high concentrations of total solids and chemical oxygen demand (COD) of the digester effluent necessitate further treatment before final disposal[3].

Development of an aquatic plant system for nutrient recovery from liquid waste may result in purification of the digester effluent while producing another value added product[5,6]. A hydroponic system for the intensive production of forage crops using commercial fertilizer was developed by Ghaly[7]. The system was also operated successfully using a diluted animal manure (2 % solids) without any commercial fertilizer[8]. Optimizing the hydroponic system for purification of the effluent from anaerobic digesters and production of forage crops may have both economic and environmental advantages. Combining anaerobic digestion and hydroponic technologies may serve the double purpose of reducing the pollution potential of animal manure and producing energy and forage crops,

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thereby helping to preserve surface water and improve the economics of farming operation.

The aim of this study was to evaluate the effectiveness of a hydroponic system for purifying the effluent from an anaerobic digester operating on dairy manure while growing wheat as a forage crop for use as an animal feed. The specific objectives were to: (a) determine the quantity of wheat seeds that will provide the optimum filtration of the waste material, (b) determine the optimum waste application rate that will provide the plant nutrients requirement for growth, (c) investigate the effect of light duration on the crop growth and yield, and (d) evaluate the pollution potential reduction of the waste as measured by the reductions in chemical oxygen demand (COD), solids and nitrogen concentrations.

EXPERIMENTAL APPARATUS

The hydroponic system (Fig. 1) consisted of a frame, growth troughs and aeration, lighting, cooling, waste application, supernatant collection and control systems. The frame was constructed of angle iron with a width of 244 cm, a depth of 41 cm and a height of 283 cm. The sides, back and the top were covered with 0.6-cm-thick plywood sheets. The frame consisted of three shelves (76 cm apart), each shelf was divided vertically into two cells by dividers made of 1.2 cm thick plywood sheets. This provided a better control of the light and feeding.

The hydroponic system has six growth troughs. Each trough was made of galvanized steel and was divided into three compartments. Each compartment held a tray that acted as the plant support medium and was made with a wire-mesh base (16 openings/cm^2) and 5 cm high metal sides. The trays were positioned in the troughs so that the plant roots were in contact with the liquid waste. This was done by means of four supports welded into the corners of each compartment, 5 cm below the top edge of the trough. An outlet from each compartment allowed the supernatant from that compartment to be collected separately. The dimensions of the each trough and plant supporting tray are shown in Fig. 2.

An aeration unit was installed in each compartment to provide oxygen to the immersed roots of the growing crops. The air flow from the main supply to the manifold on each shelf was controlled by a pressure regulator (Model 129121- 510, Aro, Brayn, OH). Six aeration units were connected to a manifold on each shelf using plastic tubing of 0.75 cm outside diameter. Small screw valves mounted on each manifold were used to control the airflow to each aeration unit, which consisted of a main tube with three perforated stainless steel laterals coming off it at right angles to the main. The tubing had an outside diameter of 0.6 cm. Each lateral was approximately 30 cm long, whereas the main was 26.5 cm long.

The lighting system was designed to provide approximately 430 hlx (19280 lumen per trough). This was achieved by a mixture of fluorescent and incandescent lamps. Six 40-W cool white fluorescent lamps (122 cm in length) and two 100-W incandescent bulbs were fastened above each trough. The lights were controlled by an electronic circuit, which was set to provide the required number of hours of light per trough per day.

A cooling system was designed to continuously remove the heat produced by the lamps to avoid heating of the wastewater on the upper and middle shelves. For each of these two shelves, a 5 cm diameter PVC pipe, having 6 mm diameter holes spaced 6 cm apart and facing out, was placed under the backside of the troughs. Two metal blocks placed under each trough provided a 5 cm space between the trough and the lighting system of the shelf below it. A 5 cm diameter PVC pipe was attached vertically to the left side of the frame and acted as manifold, through which air was blown by means of motor driven fan (Model AK4L143A type 821, Franklin Electric, Bluffton, IN).

The waste application system consisted of a control system, a feeding tank and a pump. A 100 L feeding tank was used for storing the effluent from the anaerobic digester. A mixing shaft, with a 40 cm diameter impeller, was installed through the center of the cover of the feeding tank to agitate the wastewater in the tank. Four 2.5 cm baffles were installed vertically along the inside wall of the tank to promote complete mixing. A 1 hp motor (Model NSI-10RS3, Bodine Electric, Chicago, IL) was mounted on the tank cover to drive the mixing shaft and impeller.

A variable speed pump (Model 110-23E, TAT Pumps, Logan, OH) with a capacity of 138 cm^3/revolution. was used to transfer the wastewater from the feeding tank to the applicators through a manifold (PVC pipe of 2.5 cm outside diameter) connecting a system of feeding tubes to six wastewater applicators through six solenoid valves. The waste material was pumped from the feeding tank to the waste applicators through the solenoid valves that controlled the amount of waste material fed to each cell. Each wastewater applicator was fabricated from stainless steel pipe with holes punched along the lower edge to allow the wastewater to flow out. The waste material

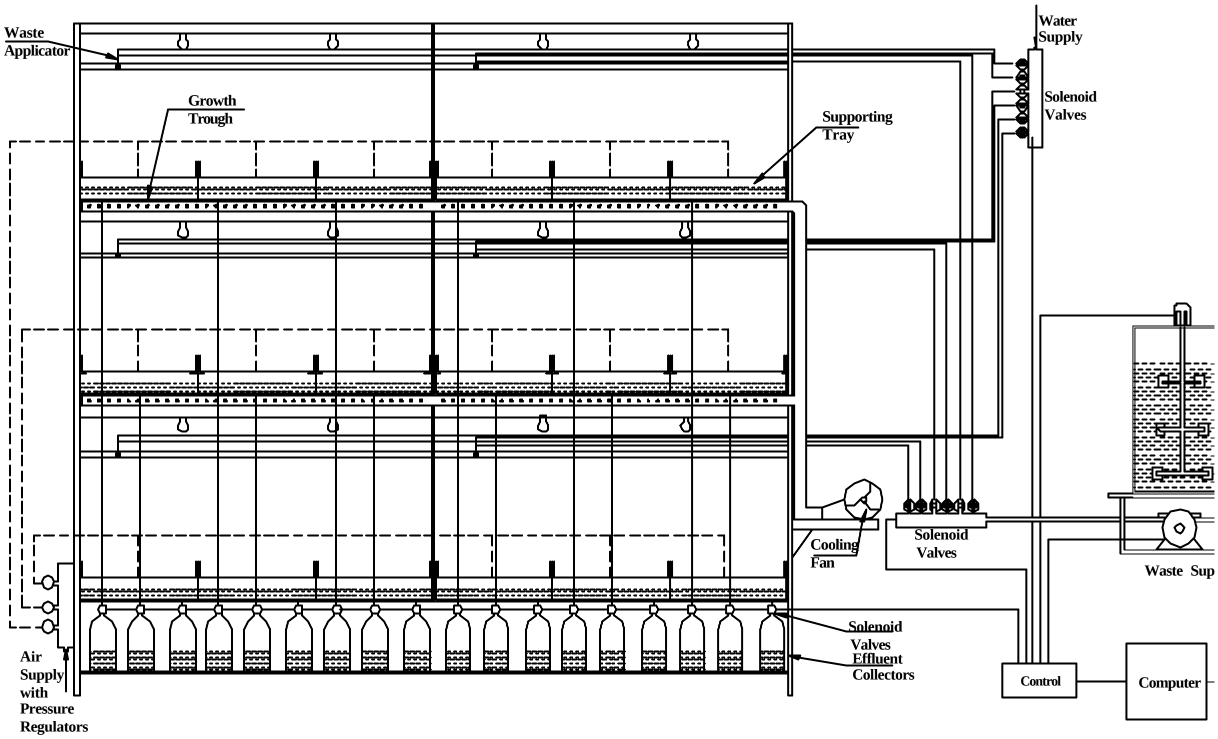

Fig. 1: Experimental setup

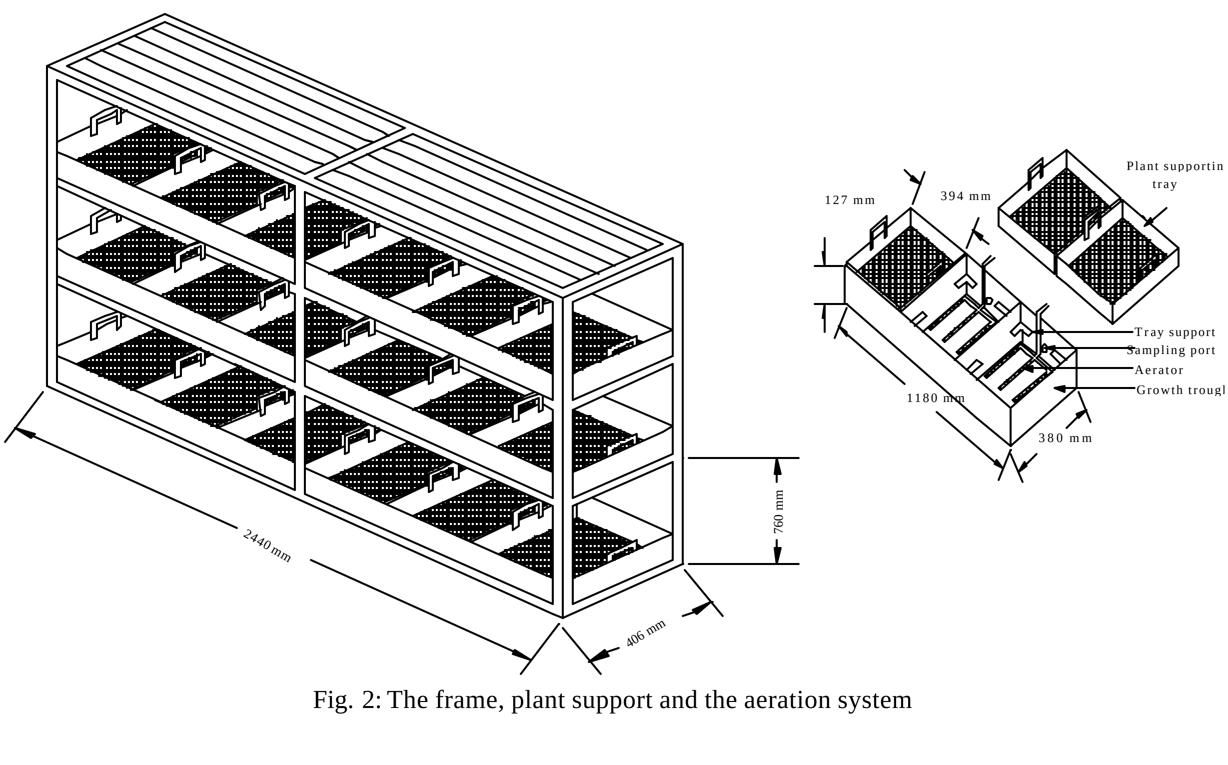

Fig. 2: The frame, plant support and the aeration system

entered the applicator at the center of the top edge. To overcome the problem of clogging, a water line with six solenoid valves attached to the applicator was used to flush out the applicator after feeding periods. The waste application system was fully automated and consisted of a motor-driven pulley arrangement on each shelf to which the applicator tube was attached. The motors (Sigma Model 20-3424SG- 24007, Faber Industrial Technologies, Clifton, NJ) ran at 6 rpm and were controlled by an electronic circuit. The system was set up so that each applicator traveled 122 cm (three tray length). When a guide on an applicator hit a micro switch located at each end of the shelf, the motor stopped, waited a few seconds and then reversed and the applicator traveled in the opposite direction. This process continued for the designated feeding time, which was controlled by computer.

The supernatant from each tray was collected in separate containers (2.7 l each) located at the bottom of the system by means of tubes attached to the outlet pipes of the compartments. The outlets were connected to plastic tubes of 1 cm outside diameter, which passed through a solenoid valve. Prior to feeding, the outlet tubes were closed using solenoid valves so that the fresh waste material was retained in the compartments to allow time for the plants to assimilate the fresh nutrients being added.

A computer was used to operate and control the various components of the hydroponic system. A basic computer program allowed the user to configure the operating frequency and duration of lighting system, waste application system and supernatant collection system. The computer was connected to a data coordinator, which had 24 digital output ports and 24 digital input ports. The digital output ports were connected to electronic circuits, which were responsible for lighting system, the cooling system, the waste application and supernatant collection systems.

EXPERIMENTAL DESIGN

Seeds quantity: Three quantities of wheat seeds per tray were used in this study: 300 g (less crowded), 400g (normal covered) and 500g (overcrowded) to determine the effect of seeding rate on the crop germination and growth and pollution potential reduction.

The nitrogen, phosphorus, potassium, calcium, and magnesium requirements for the wheat are; 56, 28, 17, 7, and 7 kg/hectare, respectively[9]. These requirements are for the soil plants and were adapted for hydroponic system. The chemical analysis performed on the wastewater (Table 1) showed that the phosphorus concentration was the growth limiting nutrient. Therefore, the application rate was based on the phosphorous content of the waste. The three waste application rates of 150, 300, and 450 mL/day (which provided 15, 30 and 45 mg of phosphorous per day per compartment) were used in this study.

The system light intensity was maintained constant at 430 hlx. The wheat is usually grown in Canada during the summer months when the days are longer. The average length of day during the crop-growing period in Canada is approximately 15 h. It was decided to see whether 24 h light duration would significantly improve the crop performance over that of 12 h light duration.

EXPERIMENTAL PROCEDURE

Day 1: The required quantities of the wheat seeds were weighed and placed on the trays in the growth troughs. The solenoid valves controlling the outlet tubes were turned off, and each compartment was filled with water to a level such that the seeds were in contact with the water but not submerged.

Day 2 – 7: The germination rate of seeds was observed and recorded daily. The seedling height was measured in each tray and recorded on days 3 and 5. A water sample was taken from each compartment and stored in a fridge (at 4 ^{o}C) in a labeled bottle for chemical analyses.

Day 8: The seedling height was measured in each tray and recorded. A water sample was taken from each compartment before waste application started and stored in a labeled bottle for chemical analyses. The required amount of waste materials was applied to each compartment.

Day 9 – 19: The crop height was measured and recorded on days 10, 14 and 18. Wastewater application continued on daily basis. A water sample was taken from each compartment before waste application and stored in the fridge (at 4 ^{o}C) in a labeled bottle for chemical analyses. The solenoid valves were then opened to allow the effluent to exit through the outlet tubes, then closed before the waste application started.

Day 22: The experiment was terminated. The crop height was measured and recorded. The cumulative volume of effluent in each bottle was measured and a water sample was taken and stored for chemical analyses. Each tray was removed from its compartment with the crop and allowed to drain. It was then weighed and the weight of the tray was subtracted from the total weight to obtain the weight of the crop.

Table 1: Chemical analysis of the wastewater

Parameter	Concentration (mg/L)
Total solids	14090
Suspended solids	2425
Chemical Oxygen Demand	14690
Ammonium Nitrogen	500
Nitrite nitrogen	0
Nitrate nitrogen	0
Phosphorous	106
Potassium	900

Table 2: Germination and seedlings height at the end of germination period

Seed Rate (g)	Light Duration (h)	Germination (%)	Seedlings Height (cm)
300	12	90	4.0
	24	89	3.0
400	12	89	4.5
	24	90	3.5
500	12	89	5.0
	24	89	5.0

Table 3: Wheat crop height and yield at harvest

Seed Rate (g)	Light Duration (h)	Waste Application Rate (mL/day)					
		300		600		900	
		H	Y	H	Y	H	Y
300	12	37.0	1.79	37.0	1.98	38.0	2.42
	24	12.0	0.33	18.0	1.18	30.0	2.60
400	12	37.0	2.45	37.0	2.74	38.0	3.65
	24	26.0	1.22	26.0	2.01	32.0	2.82
500	12	37.0	2.71	38.0	2.93	37.0	3.51
	24	30.0	1.46	30.5	2.12	33.0	2.97

- Values are the average of three measurements

H: height (cm)
Y: yield (kg)

Chemical analyses: The total solids, nitrite, nitrate, ammonium, chemical oxygen demand (COD) analyses were performed on the water samples to determine the reduction in pollution potential of the wastewater. The analyses were carried out according to the procedures described in the Standard Methods for Examination of Water and Wastewater[10].

RESULTS AND DISCUSSION

Seed germination: Within 24 h of placing the wheat seeds onto the germination trays, they started swollen and began to geminate. By day 3, the radicale and plumule had broken through the seed coat and were visible on most of the seeds. By day 5, the root mat was starting to develop and the seedlings had grown approximately 1 - 2 cm in height. At the end of germination period (first 7 days), 89-90% of seeds had germinated and the seedlings were 3 - 4 cm in height (Table 2). Neither the light duration nor the seed density had any effect on seed germination.

Renault et al[11] reported that during seed germination, plants are particularly sensitive to their chemical environment. Bewley and Black[12] stated that as seeds start to take up water during germination, there is a rapid leakage of solutes, sugars, organic acids, ions, amino acids, proteins and growth enzymes (such as gibberellins and cytokinins) into the medium, all of which affect the quality of the growth medium. However, little is known about the effects of these compounds on the processes of seed germination[13]. Therefore none of these compounds was measured in this study.

Table 4: Combined nutritional requirements for maintenance and milk production for dairy cow[22]

Item	Value@
Total digestible matter (g/Kg)	220 -230
Crude fibre (g/Kg)	120-340
Crude fat (g/Kg)	10-136
Total digestible energy (MJ/Kg)	32.7-33.9
Crude protein (g/Kg)	7.3-7.8
Macroelements (g/Kg)	
Phosphorus	0.25-0.38
Potassium	0.51-1.07
Calcium	0.06-0.22
Sodium	0.10-0.20
Chloride	0.13-0.29
Microelements (mg/Kg)	
Magnesium	0.13-0.20
Manganese	13-40
Iron	18598.00
Copper	39373.00
Zinc	21-55
Selenium	1.5-3.0
Iodine	0.4-0.5
Cobalt	0.10-0.110
Sulphur	0.15-0.20

@ Per Kg body weight

Information on the literature regarding the effect of light on seed germination are contradictory. Evans[14] stated that light does not affect wheat germination. Mata and Casasola[15] reported that germination was not affected by light but the inundation level had a significant effect. Kambizi et al[16] reported that germination under alternating light and dark period was significantly higher than under continuous light or continuous darkness. These authors indicated that seeds may depend on light for germination but exposure to regimes of alternating temperature may probably suppress the effect of the photoperiod.

Crop growth and yield: The crop height and yield results at harvest are presented in Table 3. There are conflicting reports in the literature regarding the effect of seed density on the performance of plants. Ghaly et al[17] reported that the seed density did not seem to affect plant height or the growth rate. Horii et al[18] reported that the seeding rate affected the crop growth and yield. However, in this study the seeding rate did not affect the plant height but had significant effect on crop yield.

The crops exposed to 12 hour light duration grew faster and produced higher yields than those exposed to continuous light. This could be due to the effect of heat resulting from the lighting system. The crops exposed to 12 h light grew to a height between 37 and 38 cm with a yield in the range of 1.79 - 3.65 kg per tray. The plant exposed to 24 h grew to a height between 12 and 33 cm with a yield in the range of 0.33 - 2.97 kg per tray. Cardwell et al[19] stated that light is essential for plant growth and plant growth is generally affected by the intensity and duration of light. Decoteau[20] reported that as the light intensity and/or duration increased, photosynthesis rates increased initially up to a limited level (saturation point) and further increases in light intensity did not result in a further increase in the photosynthesis rate. Mackenzie[21] reported that the crop exposed to the 12 h light duration produced higher yield and had a healthy growth than that exposed to the continuous light. The author suggested that the continuous high temperature in the vicinity of the lights could have been responsible for the poorer performance.

Increasing wastewater application rate slightly increased the plant height. The plants receiving the 300 mL of waste per day application rate grew slowly and did not have a healthy appearance. The plants receiving 600 mL per day application rate appeared healthy during the first seven days. The plants receiving the highest waste application rate (900 mL/day) appeared healthy and grew the fastest. The final results indicated that the trays receiving the lowest application rate produced the smallest yields of wheat crop. Mackenzie[21] reported similar results.

A treatment combination of a wastewater application rate of 900 mL/day, a seeding rate of 400 g/ tray and 12 hour light duration gave the best results for crop yield (3.65 kg of wheat forage per tray). With

Table 5: Comparison of ingredients of hydroponically produced wheat forage to these of commonly used field forages in feeding of cattle in North America[23]

Item	Hydro-ponically produced Wheat	Field Forge Crop					
		Alfalfa	Timothy grass	Blue grass	Birds foot	Orchard grass	Wheat pasture
Dry matter %	22	24	26	36	36	24	21
Carbohydrates (g/Kg)	330	340	360	400	360	340	380
Crude fibre (g/Kg)	65	270	310	270	270	300	180
Crude fat (g/Kg)	93	30	38	39	39	40	40
Total digestible energy (MJ/Kg)	187	157	167	180	180	170	187
Crude protein (g/Kg)	288	190	110	150	150	140	200
Macroelements (g/Kg)							
Phosphorus	9	2.7	2.8	3	3	3	3.6
Potassium	3500	26	19	19	26	26	31
Calcium	2.9	13.5	4	3.7	3.3	3.3	3.5
Sodium	3.2						
Chloride	1900	4	5.7	4.2	4.1	4.1	6.7
Microelements (mg/Kg)							
Magnesium	3040						
Manganese	98						
Iron	205						
Copper	6						
Zinc	299	18	28	25	21	21	21
Boron	0.8						
Selenium	0.1						
Iodine	0.5						
Cobalt	0.1						
Sulphur	0.2	2800	1500	1900	1900	2000	2200

Note: According to the author the organic constitutionals can vary by as much as $\pm$5%, the mineral constitutionals can vary by as much as $\pm$ 30% and the energy values can vary by up to $\pm$10%

Table 6: The solids, COD and NH_4-N concentrations (mg/L) in the wastewater at the end of germination period

Seed Rate (g)	Light duration (h)	Solids	COD	NH_4-N
300	12	100	95	2
	24	200	267	2
400	12	131	101	2
	24	250	294	2
500	12	155	178	3
	24	290	338	3

? Values are the average of three measurements thirteen harvests per year, a total yield of 3160 tonnes per hectare per year is possible. This is more than 98 times greater than the yield obtainable from filed growth of the conventional forage of 245 tonnes per hectare per year.

Nutritional value: The ranges of combined nutritional requirements for maintenance and milk production for dairy cows are shown in Table 4[22]. The composition of the hydroponicaly produced wheat forage and several field forage crops are shown in Table 5[23]. Not only the hydroponic production of wheat as a forage crops exceeded (98 fold) field production of forage crops but the wheat forage crop produced in this study had a superior nutritional value compared to the other field forage crops. It had higher digestible energy, higher carbohydrates, fat, protein and mineral contents and less crude fiber. It provides some of the macro and micro nutrients (Sodium, Magnesium, Manganese, Iron, Copper, Boron, Selenium, Iodine, and Cobalt) that are below the detection limits in the field forage crops. Wheat also had much less sulfur content compared to those in the forage filed crops

Effect of seed germination on water quality: The seed were germinated in water for 7 days. The total solids, COD, ammonium nitrogen concentrations resulting from the germination process are presented in Table 6.

The solid concentration in the wastewater increased with time during the germination period due to the release of dissolved and suspended solids (sugars, organic acids, ions, amino acids, protein, and enzymes) from the seeds as a result of the germination process[17]. Increasing the quantity of seeds increased the amount of solids released by the seeds. The values varied from 100 to 290 mg/L, depending on the seeding rate and light duration. It seems also from the results that the light affected the enzymatic activity which caused higher solid concentrations under the 24 hour light duration during the germination period.

The chemical oxygen demand (COD) concentration in each compartment increased with time during the seed germination period due to the release of enzymes and other growth substances. The values ranged from 95 to 338 mg/L, depending on the seeding rate and light duration. The increase in COD concentration observed at the end of the germination period was higher with higher seeding rates and the 24 hour light duration.

The ammonium nitrogen in the growth medium at the end of germination period was increased by 2 to 3 mg/L. During the germination period, the organic nitrogen released from the seeds (proteins and amino acids) was converted into ammonium by a biological process called mineralization or ammonification. In addition, the solutes released by the seeds may have stimulated the growth of nitrogen fixing organisms, thus increasing the concentration of NH_4 in the growth media[12]. The conversion of N_2 to NH_4 has a large metabolic energy requirement and the sugars released from the seeds would serve as a ready source of energy for the nitrogen fixing process[24].

Effluent characteristics

Total solids: Table 7 shows the concentration of solids and the solid removal efficiency at the harvest time. During the growth period, the solids concentration declined with time due to the development of the crop roots and increased filtration capacity of the root mat. The root system was also capable of absorbing dissolved solids as plant nutrients.

The results showed no effect of the seeding rate on the solid removal efficiency. This could be due to the fact that most of the solids in the effluent (83.0%) were in the soluble form. Mackenzie[21] reported that the solid removal efficiency remained approximately the same for a given waste application rate regardless of the seeding rate. However, other researches reported significant impact of the seeding rate on the solid removal efficiency. Rababah and Ashbolt[25] reported that using more plants in the hydroponic system achieved higher reduction in the nutrient level in the wastewater. Ghaly et al[17] stated that total solids reduction in the effluent was influenced by the plant type and seed density.

The effluent solid concentration at harvest was in the range of 1940 - 4790 mg/L with a removal efficiency of 66.0 – 86.2 % for the 12 hour light duration and in the range of 1430 - 4150 mg/L with removal efficiency of 70.6 – 89.9 % for the 24 hour light duration, depending on the seeding rate and wastewater application rate and light duration. There are no reports in the literature on the direct effect of light on the solid removal efficiency. However, the results obtained from this study showed that plants grow much faster and produced higher yield under 12 hour light duration and as a result their root system filtered higher percentage of the suspended soils and removed higher percentage of the dissolved solids.

The solids removal efficiency obtained was inversely proportional to the wastewater application rate. The highest removal efficiencies were obtained in the trays receiving the lowest waste application rate.

Table 7: Total solid concentration and removal efficiency at harvest

Seed Rate (g)	Light Duration (h)	Wastewater Application Rate (mL/day)					
		300		600		900	
		Solid Concentration (mg/L)	Removal Efficiency (%)	Solid Concentration (mg/L)	Removal Efficiency (%)	Solid Concentration (mg/L)	Removal Efficiency (%)
300	12	2190	84.5	2890	79.5	4130	70.7
	24	1450	89.7	2700	80.8	3600	74.5
400	12	1940	86.2	3310	76.5	3425	75.7
	24	1430	89.9	2630	81.3	3570	74.7
500	12	2090	85.2	2700	80.8	4790	66.0
	24	1970	86.0	2960	79.0	4150	70.6

Values are the average of three measurements
The initial solid concentration = 14090 mg/L

Table 8: Chemical Oxygen Demand concentration and removal efficiency at harvest

Seed Rate (g)	Light Duration (h)	Wastewater Application Rate (mL/day)					
		300		600		900	
		COD Concentration (mg/L)	Removal Efficiency (%)	COD Concentration (mg/L)	Removal Efficiency (%)	COD Concentration (mg/L)	Removal Efficiency (%)
300	12	1125	92.3	1600	89.1	2666	81.9
	24	1481	89.9	1603	89.1	2203	85.0
400	12	1669	88.6	2202	85.0	2073	85.9
	24	2127	85.5	1340	90.9	2061	86.0
500	12	1771	87.9	1867	87.3	1160	92.1
	24	1797	87.8	3234	78.0	3498	76.2

Values are the average of three measurements
The initial solid concentration = 14690 mg/L

Table 9: Ammonium Nitrogen concentration and removal efficiency at harvest

Seed Rate (g)	Light Duration (h)	Wastewater Application Rate (mL/day)					
		300		600		900	
		NH_4 Concentration (mg/L)	Removal Efficiency (%)	NH_4 Concentration (mg/L)	Removal Efficiency (%)	NH_4 Concentration (mg/L)	Removal Efficiency (%)
300	12	98	80.4	178	64.5	151	69.8
	24	71	85.8	140	72.0	213	57.4
400	12	91	81.8	193	61.4	122	75.6
	24	116	76.8	145	71.0	131	73.8
500	12	96	80.8	125	75.0	229	54.2
	24	140	72.0	162	67.6	207	58.6

Values are the average of three measurements
Initial ammonium nitrogen = 500 mg/L

Table 10: Nitrate nitrogen concentration (mg/L) at the end of germination (day 7) and growth (day 22) periods

Seed Rate (g)	Light Duration (h)	Waste Application Rate (mL/day)					
		300		600		900	
		Day 7	Day 22	Day 7	Day 22	Day 7	Day 22
300	12	1.5	5.5	1.4	5.6	1.6	10.1
	24	1.6	4.1	1.6	3.0	1.6	6.6
400	12	1.6	7.2	1.6	8.4	1.4	6.7
	24	1.4	3.3	1.6	4.2	1.6	8.0
500	12	1.6	7.1	1.5	4.4	1.5	10.1
	24	1.5	3.8	1.5	6.1	1.4	8.2

Values are the average of three measurements
Initial nitrate concentration = 0 mg/L

The removal efficiency was in the range of 82.0 – 89.9 % for the 300 mL/day wastewater application rate, in the range of 71.2 – 82.2% for the 600 mL/day wastewater application rate and in the range of 66.0 – 75.7 % for the 900 mL/day wastewater application rate. Bouzoun et al[26] reported an inverse relationship between wastewater application rate and solids removal efficiency when using a nutrient film technique for wastewater treatment. Mackenzie[21] reported that the lower solids removal efficiencies corresponded with higher initial solid concentrations. Lin et al[27] achieved 90% reduction in aquaculture wastewater suspended solids using subsurface flow wetland planted with reed (*Paspalum vaginatum*). Brix[5] stated that the reduction in suspended solids caused by macrophytes is attributed to filtration of solids by the plant tissue. Ghaly et al[17] stated that not only the plants filtered out all the solids in the wastewater during the growth period, but also removed between 24.2% and 88.0% of the materials released by the seeds during germination.

Chemical Oxygen demand: The COD concentration decreased significantly during the growth period (Table 8) because the crop root system was fully developed and the root filtration capacity of suspended solids and absorption of dissolved nutrients increased. The light duration did not seem to have a significant effect and the COD removal efficiency. The results also showed no significant effect of the seeding rate on the COD removal efficiency except for slight decrease in the removal efficiency with the increase in the seeding rate at the 300 mL/day wastewater application rate. Bouzoun et al[26] stated that seeding rates and root density appeared to have been major factors in COD removal, the greater the root density the greater the removal efficiency of COD. Mackenzie[21] reported a positive relationship between the seeding rate and the effluent (COD) concentration during the germination period but found no effect of the seeding rate on the final removal efficiency.

The final COD concentration increased with the increase in the wastewater application rate and as a result the COD removal efficiency decrease. The COD concentrations at the end of the growth period ranged from 1125 to 3498 mg/L with a removal efficiency in the ranged of 76.2 -92.3 %, depending on the waste application rate. Mackenzie[21] reported that the reduction in the COD was inversely proportional to the waste application rate. Gloger et al[28] compared the COD removal rate from fish wastewater by hydroponic tanks that had lettuce plants with that by aerated tanks that had no plants and reported 54% higher COD removal rate for lettuce tanks compared with tanks with no plants. Wilkie and Mulbry[29] studied the recovery of dairy manure nutrients by benthic freshwater algae and achieved a COD reduction of 95%.

Ammonium Nitrogen: Table 9 shows the ammonium nitrogen concentration and the removal efficiency at the harvest time. The plants received the lowest wastewater application rate were able to remove a greatest percentage of the ammonium nitrogen (72.0 – 85.8%) compared to those that received the highest wastewater application rate (57.0 – 75.6 %). Bouzoun et al[26] stated that the removal efficiency of the total nitrogen increased when the flow rate of wastewater applied to the hydroponic system was decreased. Mackenzie[21] reported that the plant receiving the lower wastewater application rates were able to remove the greater percentage of the ammonium nitrogen than those receiving the higher application rates. Schaafsma et al[30] reported that a constructed wetland system built to treat wastewater from a dairy farm removed a significant amount of ammonium (56%). No effects of the seeding rate, light duration and fungicide application on the ammonium nitrogen removal efficiency were observed.

Nitrite and Nitrate Nitrogen*:* Because the system was aerated, some of the ammonium present in the wastewater was converted to nitrite and nitrate by the nitrification process as follows [31].

$$NH^{+}_{4}+1.5O_2 \xrightarrow{\text{nitrosamines}} NO^{-}_{2} + H_2O + 2H^{+} \quad (1)$$

$$NO^{-}_{2}+ 0.5O_2 \xrightarrow{\text{nitrobacter}} NO^{-}_{3} \quad (2)$$

The nitrite nitrogen concentration in the wastewater during the germination and growth periods was zero while the nitrate nitrogen concentration ranged from 1.4 to 1.6 mg/L by the end of germination period and from 3.0 – 14.2 mg/L by the end of the experiment (Table 10). These results showed that the conversion rate of nitrite to nitrate by the *nitrobacter* bacteria was much faster than the conversion rate of ammonium to nitrite by *nitrosamines* bacteria. Schaafsma et al[30] found a significant increase in nitrate concentration (82%) during the treatment of dairy wastewater in a constructed wetland. Ghaly et al[17] reported that the ammonium was oxidized into nitrite and then into nitrate in a hydroponic system during the plant growth period of cereal crops and the concentrations were dependent on the quantity and the type of seeds. The authors also stated that nitrite and nitrate nitrogen concentrations in a hydroponic system treating aquaculture wastewater increased with time during germination period, then decreased during the plant growth period and the final concentration depended on the seed quantity.

CONCLUSIONS

A hydroponic system was developed and used for the purification of anaerobic digester effluent and production of forage crops. The hydroponics system was capable of producing a wheat forage crop in 21 days while purifying the partially treated dairy manure. The removal efficiencies of the solids, chemical oxygen demand and ammonium were in the ranges of 66.7 - 89.9 %, 79.8 - 92.3% and 54.2 - 85.8 % respectively. The removal efficiencies were reduced when the wastewater application was increased as a result of overloading the system with nutrients. The light duration did not have a significant effect on plant growth or the purification process. A treatment combination of a wastewater application rate of 900 mL/day, a seed rate of 400 g/ tray, and 12 hour light duration gave the best results for crop yield (3.65 kg of wheat forage per tray) with removal efficiencies 75.7. 85.9 and 75.6 % for solids, COD and NH_4-N, respectively. The crop yield was 98 times that of the conventional forages of 245 tonnes per hectare produced in the field annually. The nitrate nitrogen concentration (6.7 mg/L) in the final effluent was below the Canadian Guidelines for Health of 10mg/L.

ACKNOWLEDGEMENTS

This research was funded by the Natural Science and Engineering Research Council (NSERC) of Canada.

REFERENCES

1. Ghaly, A. E. and E.A. Echiegu, 1995. Performance evaluation of intermittent flow continuose mix anaerobic reactor operating an dairy manure. Biomass and Bioenergy, 4(3): 185-197.
2. Ghaly, A. E. and R. Ben- Hassan, 1989. Continuous production of biogas from dairy manure using an innovative no – mix reactor. Applied biochemistry and biotechnology journal, 20(3): 541-559.
3. Ghaly A. E., S. S. Sadaka and A. Hazzaa, 2000. Kinetics of an intermittent flow continuous mix anaerobic reactor. Energy source, 22(6): 1-18.
4. Ghaly A. E., 1996. A comparative study of anaerobic digester of chees whay and dairy manure in a two stage reactor. Bioresource technology, 58(1): 61-72.
5. Brix, H., 1997. Do macrophytes play a role in constructed wetlands? Water Science and Technology, 35(1): 11 –7.
6. Jiang, Z. and Z. Xinyuan, 1998. Treatment and utilization of wastewater in the Beijing zoo by an aquatic macrophyte system. Ecological Engineering, 11(1):101-110.
7. Ghaly, A.E., 1985. A modified hydroponic system for the intensive production of forage crops using commercial fertilization. Technical report, Technical University of Nova Scotia, Halifax, NovaScotia.
8. Ghaly, A.E., J. Pyke, C. Sambrook and E. Echiegu, 1988 A nutrient film system for the intensive production of forge crops from anaerobically treated animal manure. Paper presented at the annual meeting of NAR- ASAE, Saint Mary's University, Halifax, Nova Scotia. ASAE paper No. NAR - 88-207.
9. Atlantic Provinces, 1991. Field Crop Guide for the Atlantic Provinces. Atlantic Provinces Agricultural Series, Publication No. 100, Halifax, Nova Scotia.

10. APHA, 1998. Standard Methods for Examination of Water Wastewater. American Public Health Association, Washington, DC.
11. Renault, S., J. J. Zwiazek, M. Fung, and, S. Tuttle, 2000. Germination, growth and gas exchange of selected boreal forest seedlings in soil containing oil sands tailings. Environmental Pollution, 107(1): 357-365.
12. Bewley, J. D. and M. Black, 1985. Seeds: physiology of development and germination. Plenum Press, New York, New York.
13. Uangar, I. A., 1996. Salinity, temperature, and growth regulator effects on seed germination of *Salicornia europaea.* Aquatic Botany, 3(12): 329-335.
14. Evans, L. T., 1975. Crop Physiology: Some Case Histories. Cambridge University, Cambridge.
15. Mata, D. I. and P. M. Casasola, 2005. Effect of in situ storage, light, and moisture on the germination of two wetland tropical trees. Aquatic Botany, 83(2): 206 – 218.
16. Kambizi, L., P. O. Adebola and A. J. Afolayan., 2006. Effects of temperature, pre-chilling and light on seed germination of Withania Somnifera, a value medicinal plant. South Africa Journal of Botany, 72(1): 11-14.
17. Ghaly, A.E., M. Kamal and N. S. Mahmoud, 2005. Phytoremediation of aquaculture wastewater for water recycling and production of fish feed. Environment International, 31(1): 1-13.
18. Horii, A., P. McCue and K. Shetty., 2007. Enhancement of seed vigor following insecticide and phenolic elicitor treatment. Bioresource Technology, 98(3): 623-632.
19. Cardwell, V. B., 1984. Seed Germination and Crop Production: Physiological Basis of Crop Growth and Development. American Society of Agronomy, Madison, Wisconsin.
20. Decoteau, D. R., 2005. Principles of Plant Science: Environmental Factors and Technology in Growing Plants. New Jersey, New Jersey.
21. Mackenzie, C. A., 1989. Purification of partially treated dairy manure through the intensive production of forage crops. MA.Sc. Thesis. Technical University of Nova Scotia, Halifax, Nova Scotia.
22. Barney, H., 1992. Nutrients requirements for dairy cattle. Technical report, Animal Science Department, University of Florida, Gainesville, Florida.
23. Perston, 2002. Feed Composition Guide. http:// images, beef.mag.com
24. Mayer A.M., and A. Doljakoff – Mayber, 1975. The germination of seeds. Pergamon Press, New York, New York.
25. Rababah, A. and N. J. Ashbolt., 1999. Innovative production treatment hydroponic farm for primary municaple sewage. Pergamon Press, New York, New York.
26. Bouzoun, J. R., C. J. Diener and P. L. Bulter, 1982. Pilot scale evaluation of the nutrient film technique for wastewater treatment. U.S. army crop of engineers special report, Las Vegas, Nevada.
27. Lin Y., S. Jing, D. Lee and T. Wang, 2002. Removal of solids and chemical oxygen demand from aquaculture wastewater with a constructed wetland system in the startup phase. Water and Environmental Research, 74(1): 136–41.
28. Gloger K.C., J. E. Rakocy, J. B. Conter, D. S. Bailey, W. M. Cole and K. A. Shultz., 1995. Contribution of lettuce to wastewater treatment capacity of raft hydroponics in a closed recirculating fish culture system. In: Proceedings of Aquacultural Engineering and Waste Management, Aquaculture Expo VIII and Aquaculture in the Mid-Atlantic Conference (Timmons, M.B., editor), Washington DC, pp.272– 300.
29. Wilkie, A. C. and W. W. Mulbry, 2002. Recovery of dairy manure nutrients by benthic freshwater algae. Bioresource Technology, 84(1): 81–91.
30. Schaafsma, J. A., A. H. Baldwin and C. A. Streb, 2000 An evaluation of a constructed wetland to treat wastewater from a dairy farm. Ecological Engineering, 14(2): 199 – 206.
31. Olsson, M. O. and U. Falkengren, 2000. Potential nitrification as an indictor of prefertential uptake of Ammonium or Nitrate by plant. Annals of botany, 85(3): 299 – 305.