

**ECONOMICS AND FEED VALUE OF INTEGRATING
DUCKWEED PRODUCTION WITH A SWINE OPERATION**

by

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ABSTRACT

The large production of livestock on the Southern High Plains each year results in needs to handle manure and wastewater. The beef and swine industries are incorporating manure waste management plans to ensure a stable environment. Aquatic plants have been used for many years as an integral part of wastewater treatment. One aquatic plant, duckweed, is providing high removal rates of nutrients and potential pollutants. Studies have reported crude protein in duckweed as high as 45%. The high crude protein values offer possibilities of incorporation into animal feeding operations.

In the formulation of swine rations, protein or more specifically amino acids are critical to growth and performance. The aquatic plant duckweed has similar crude protein levels and contains essential amino acids like lysine, threonine, and tryptophan that needed in swine rations. Experiment 1 utilized sixty-four nursery pigs in a feeding trial to determine the effects of replacing soybean meal with duckweed as the crude protein supplement. The data from the 21-day growth trial indicated there was a significant increase ($P < 0.05$) in average daily gains between the 40% and 60% replacement of soybean meal with duckweed treatments and the control treatment with no differences ($P > 0.10$) in feed efficiency. Pigs fed duckweed treatments had a long-term effect on weight gain as indicated by higher ($P < 0.025$) final slaughter weights.

In experiment 2, twelve nursery pigs were used in a metabolism trial to determine the digestibility of nutrients and dry matter (DM) of diets containing 0,

40%, or 60% duckweed. The digestibility of dry matter, crude protein, and phosphorus was the highest in the control treatments ($P < 0.05$). The duckweed treatments performed adequately for growth performance; however, the treatments did not perform well in digestibility of key environmental nutrients.

The livestock industry is faced with the important decision of wastewater treatment. This research provides information on one wastewater treatment system that produces two valuable end products: water reuse capabilities and duckweed as a feed supplement. The estimated investment will be different for each operation, but this provides livestock operators a general idea on the investment costs for incorporating the production of duckweed into the wastewater treatment system.

The estimated production yield of 1 134 kilograms per month of dried duckweed would not sustain a grower/finisher swine operation, but would provide a level of replacement in a nursery unit. The average 10-kilogram nursery pig has an approximate feed intake of 0.46 kilograms per day. The estimated yield production of 37.65 kilograms per day will provide enough duckweed for a 15% replacement level. This 15% replacement of soybean meal with dried duckweed would reduce operating costs needed to sustain a nursery swine operation and research indicated further benefit from increased final slaughter weights.

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CHAPTER I

LITERATURE REVIEW

Introduction

The large production of livestock on the Southern High Plains each year results in a greater need to handle manure and wastewater. The average 340-kilogram feedyard steer will produce 27 kilograms of waste per day per animal unit, and in contrast the average grower pig will produce 29 kilograms of waste per day per animal unit. According to the Natural Resource Conservation Service's Agricultural Waste Management Field Handbook, an animal unit is the waste production from livestock that is expressed in pounds per day per 1000 pounds of livestock weight. The beef and swine industries are concerned with the quantities of manure produced each year, and are incorporating manure waste management plans to ensure a stable environment. The wastes of livestock contain high levels of nitrogen, phosphorus, and total solids. Waste constituents are also highly soluble and can move rapidly through the soil profile to the groundwater sources, which has become a serious water quality concern. Historically, livestock waste has been applied to crop and pasture land, but the amount of agricultural land in production is diminishing. Therefore the need for treatment of livestock waste is essential to the future quality of water (Senate Agriculture Committee, 1997). The environmental complications of animal

feeding operations have become increasingly important as the twenty-first century approaches.

Swine Industry

The pork industry is increasing commercial production each year. In 1997, the National Agricultural Statistics Service indicated that the number of hogs represent 14% of all livestock and poultry sold in the United States. The National Hog Farmer Magazine (1998) reports that Oklahoma marketed 203,439 pigs in 1987 and the next year 1,100,000 pigs were marketed. Although, the total number of swine operations has dropped, the number of pigs is produced annually has remained the same. The 1997 Census of Agriculture reported 46,353 swine operations in the United States. Complex changes have occurred in production practices and the region in which the production is taking place. Major swine operations are relocating to suitable regions for production. The Southern High Plains is has optimal climatic conditions for such operations. The region has lower amounts of average yearly rainfall and humidity. The industry also relocated to take advantage of access to grain and slaughter facilities. Approximately 3% of the confinement operations produce more than 50% of the nation's swine (Senate Agriculture Committee, 1997). These large-scale confinement operations produce large amounts of manure and wastewater. The estimated annual solid manure production by hogs amounts to 116,652,300 tons (Senate Agriculture Committee, 1997). The composition of swine waste is

represented in Table 1.1. A vast amount of research is being conducted to provide accurate data to relieve some environmental pressures on the industry. The main complaint from surrounding neighbors is the odor from the large confinement facilities. Odors are the direct result of insufficient or absence of waste treatment systems. The main methods of swine manure management are storage tanks and anaerobic lagoons. Both storage units and anaerobic lagoons can lead to increased odor problems. Simple design techniques can reduce the odors from large swine operations. The environmental pressures have become the main focus of the swine industry for the next century.

Environmental Pressures

The recent target of environmental concerns has been large animal feeding operations. The Environmental Protection Agency (EPA) believes that the agriculture industry contributes to the degradation of 60% of the nation's waters (Senate Agriculture Committee, 1997). The large-scale swine confinement operations are considered an animal feeding operation or a concentrated animal feeding operation (CAFO). A CAFO is defined as an animal feeding operations where greater than 1000 animal units are confined for over 45 days and no crop growth can be sustained. Operations with more than 1000 animal units must have National Pollution Discharge Elimination System (NPDES) permits for stringent effluent guidelines. The Clean Water Act of 1972, under section 402, sets discharge limitation guidelines on CAFOs. The permits

ensure that the minimum water quality standards are being met. Animal agriculture produces non-point source (NPS) and point source pollution. NPS is defined as pollutants that affect surface waters from unknown sources. Point source pollution is the discharge of pollutants into navigable waters by means of a man-made device. A CAFO is specifically classified as a point source. This particular pollution is believed to be the result of animal feeding operations' direct discharges of manure and wastewater into natural or manmade waterways. An animal feeding operation does not fall under the NPDES permitting guidelines if the operation only discharges during a 25-year, 24-hour storm event. Many discharges from CAFOs occur as a result of rainfall. NPS and point source concerns include the potential for nutrient runoff into surface waters or groundwater leaching. These concerns lead to more regulations on animal feeding operations. The EPA and Natural Resource Conservation Service (NRCS) have recently released the Final Unified National Strategy for Animal Feeding Operations. The strategy calls for animal feeding operations to develop and implement Comprehensive Nutrient Management Plans (CNMPs) into their waste-management systems. CNMPs include feed management, manure treatment, land application, land management, and record keeping. The recommendation to develop and implement CNMPs is voluntary; however, the goal of the strategy is to have all animal feeding operations develop the CNMPs by the year 2009 (Final Unified National Strategy for Animal Feeding Operation, 1999). The plans will reduce or eliminate the environmental risks. The EPA's

goal focuses on compliance issues associated with the Clean Water Action Plan (CWAP) of 1998, which will expand and strengthen environmental efforts to enforce water quality and improve waste treatment systems. The Final Strategy was developed as a direct response to the CWAP. The regions and states are encouraged to voluntarily follow the guidelines in the strategy, but they are not at this point new regulations.

The rapid growth of the pork industry in Texas and Oklahoma has created concerns among their state legislatures. Texas passed stringent environmental rules in 1995 under the Texas Water Code and Texas Clean Air Act to accommodate the large operations in the Southern Plains Region. All Texas CAFOs are required to comply with the provisions of Chapter 321, Subchapter B: Commercial Livestock and Poultry Production Operations, and Subchapter K: Concentrated Animal Feeding Operations. The region also has a regulation on permit requirements in Chapter 116, Subchapter B: Control of Air Pollution by Permits for New Construction or Modification. The Texas Administrative Code established Subchapter K as a preventative goal. The wastewater produced shall be utilized in an appropriate and beneficial manner. A Pollution Prevention Plan is recommended under Subchapter K. The State of Oklahoma also has enforced strict regulations. Oklahoma requires a NPDES and state CAFO license. In February of 1998, Oklahoma enforced a one-year moratorium to slow down the expansion and creation of new swine operations.

Recent environmental regulations have forced agriculture researchers to look at animal waste management. How can the waste be used to reduce the amount of pollutants released into the environment and yet be economical to the animal feeding operation? Traditionally, disposal of manure and wastewater has been applied to crops or pasture land. This method must be accompanied with a biological waste treatment system to reduce the amount of nutrients. Nutrient contamination of groundwater is a particular concern for human health and environmental quality. The treatment systems provide initial nutrient reduction before disposal on crops. Wastewater ponds have been widely used as a natural treatment system. Another possibility for high removal rates is aquatic plants grown in natural wastewater treatment systems.

The Aquatic Plant Duckweed

As the human population increases, the need for clean water increases as well. The role of wastewater treatment is to protect the environment and human health. Researchers have studied aquatic plants for many years as integral parts of the treatment process in wastewater. The plants remove enough nutrients from the water to provide a supply of water to the agricultural industries. The nutritive value of the aquatic plants is also comparable to traditional harvested crops. One aquatic plant in particular is providing high removal rates of pollutants and showing high nutrient values. The duckweed plant has been used in wastewater treatment facilities to remove nutrients to achieve secondary

treatment. The raw material in wastewater provides an excellent medium for duckweed growth. Skillicorn et al. (1993) reported potential removal rates of 99% of the nutrients and dissolved solids present in livestock wastes. The removal rates of nitrogen play an important role in protein production. Studies have reported crude protein in duckweed as high as 45%. The crude protein of duckweed offers the possibilities of incorporation into animal feeding operations as a protein by-product feedstuff. Duckweed proteins have a greater concentration of essential amino acids and various other contents than most plant proteins.

Many factors determine the protein content of duckweed. The average protein concentration ranges from 35% to 45% (Skillicorn et al., 1993). Soybean meal contains 44% to 48% crude protein and is used extensively as a feedstuff. Duckweed has been compared with soybean meal as a protein source. The goal of this research is to explore the nutritional quality of duckweed and, in particular, the protein.

The ability to integrate a wastewater treatment system into animal feeding operations would provide many possibilities. The waste produced by a concentrated animal feeding operation would provide the appropriate medium for duckweed production. The water from the duckweed ponds can be recycled for facility cleaning or for irrigation purposes. The extra water would be advantageous to operations that are experiencing a fresh water shortage. Duckweed shows promising results in nutritive protein values and vegetative

growth production, but can a duckweed system be economical to an agricultural enterprise? Previous research will be examined to detect the optimal techniques to increase the crude protein levels of duckweed. Growth rates, management practices, and harvesting techniques influence the final percentage of protein and yield.

Duckweed Morphology

Duckweeds are tiny, free floating plants that belong to the *Lemnaceae* family. Duckweed is a flat, leaf-like plants that are only a few millimeters wide. It has unique morphology and growth characteristics. The *Lemnaceae* family has four genera and more than forty known species. *Lemnaceae* are separated into two types. The first type has one or more roots and two lateral reproductive pouches. The second type has no roots and a single reproductive pouch (Daubs, 1965). Four common genera are *Lemna*, *Wolffia*, *Spirodela*, and *Wolffiella*. These aquatic macrophytes include the smallest of all flowering plants. The *Lemna* species has been reported to measure 6-8 millimeters in size and is oval in shape. The duckweed is made up of a green vascular frond (leaf) that resembles a fusion of leaves and stems. The duckweed leaf is flat and ovoid. A steady supply of nutrients and trace elements is needed for optimal vegetative growth. The survival conditions are suitable to moderate climates of tropical and temperate zones of warm and sunny weather. Duckweed does not survive in fast-moving waters. The most important aspect of duckweed is its

exponential ability to double in mass in 2 days. The lifetime production of the duckweed plant is 1 to 2 months (Armstrong, 1997). The active meristem of the plant is constantly dividing to reproduce more fronds. Hillman and Culley (1978) reported that one frond can yield up to 10 to 20 new fronds. Leng et al. (1995) reported that an individual frond may divide ten times over a 10-day to 2-week period. Oron et al. (1984) suggested growth rates of duckweed to be 0.1 to 0.5 grams per gram per day. Many researchers have compared the vegetative growth of duckweed to bacterial and algae growth. The duckweed's ease of propagation makes it a reasonable cultivated crop.

Species selection is very important due to the different biochemical patterns of the duckweed plants. For example, each species have different photoperiods. Day length plays a major role in the production of phytochrome. The species of *Lemna gibba* is a long-day plant. Long-day plants require approximately 9 hours of darkness, in contrast to the 13 to 18 hours required by short-day plants. Oron et al. (1987) stated that *Lemna gibba* is superior to other species. This species can grow at variable temperatures of 5°C and up to 30°C. Oron and Porath (1987) suggested the same species proved to be the best duckweed for nutrient removal efficiency and growth rates. One of the best ways to select a species for a particular operation is to obtain the stock from a native species. Native species are grown in the wild and are already suited for the atmospheric climate. These native species are found on polluted waters in the area. This method of selecting duckweed stock can establish a productive stand.

Management of Duckweed

The production of duckweed is an intensive management operation. The operation regime plays a major role in protein production in a duckweed system. The regime includes pond depth, retention time, species selection and establishment, and loading rates. Duckweed proteins have a greater concentration of essential amino acids, and various other contents, than most plant proteins. There are many factors that determine the protein content of duckweed. Growth rates, management practices, and harvesting techniques can be influential in the final percentage of protein. The array of amino acids exhibited in duckweed makes the final product an alternative feed ingredient to be used in animal diets.

Retention time plays a major role in the plant's nutritive values. Oron (1990) observed that a retention time of less than 5 days showed a healthier appearance in the plants. Longer retention times can yield longer root growth and a pale green color resulting from a shortage of nutrients. Whitehead et al. (1987) reported that the highest sustainable nutrient removal efficiencies were obtained at 20-day hydraulic residence time (HRT) at a 10 % cropping rate. This particular retention time enabled the duckweed to sustain dense growth and focus on nutrient removal during the experiment. During the same experiment, high removal rates of nitrogen and phosphorus were also obtained at retention times of seven to ten days. The increased removal rates occurred only with increased cropping rates. Several reports indicated that growth rate decrease as

a result of longer retention times. Another experiment by Oron et al. (1985) reported an increased retention time was related to a lower crude protein; however, an increased level of ammonium concentration was found in the effluent. Crude protein content in *Lemna gibba* has been reported to be as high as 48.1% when grown in an ammonium concentration of 169.2 mg per liter with a retention time of 10 days. A similar study by Oron and Porath (1987) reported 97% removal efficiencies in ammonia. As shown in many experiments, retention time is an important management tool in achieving high nutrient removal rates.

The next most important aspect is harvesting techniques. The amount harvested at any given time can determine future growth and reproduction. Whitehead et al. (1987) found a 10% area per day cropping rate to be an adequate removal of nutrient concentrations in effluent. This cropping rate allowed the duckweed to maintain density while still maintaining aerobic conditions. Harvesting rates of 30% area per day caused the duckweed population to cease its growth. Duckweed must be harvested to prevent matting. Matting occurs when the duckweed gets thick in density and does not allow for oxygen or sunlight to reach the water below the surface. Skillicorn et al. (1993) recommends a harvesting rate of around 100 grams per square meter per day to maintain a healthy duckweed crop. Regular harvesting to maximize production can increase the growth rate of duckweed. The optimal cropping rate and harvesting rate will be different for each particular operation. Operations that want to maximize nutrient removal might have a longer harvest interval; whereas,

an operation that is utilizing the duckweed for a protein source might want to harvest at an earlier time to prevent root growth. .

The supply of nutrients for growth requires a great deal of attention. The first phase of a duckweed production system is the removal of solids. This process can be achieved in the primary sedimentation treatment process. The solids in raw wastewater effluent cannot be utilized by the duckweed plant. The next phase of treatment is secondary treatment. Secondary treatment is achieved by a lagoon system. Once the wastewater has gone through primary treatment and secondary treatment, duckweed production begins in a shallow pond system. Several experiments have examined the proper dilution of effluent. Skillicorn et al. (1993) stated that a rule of thumb for dilution should be 80 milligrams per liter of livestock waste. Dilutions of fresh cattle manure at levels of 5, 10, 15, and 20 grams per liter were considered by Said et al. (1979). These workers reported no statistical difference in the 10- to 20-grams per liter manure dilutions. The highest growth yield was achieved at a 6-day harvest interval at a 10-gram per liter manure dilution. Stanley and Madewell (1975) observed that optimum weekly growth of *Lemna minor* occurred from swine waste dilutions of 19 milliliter per liter. Oron et al. (1987) studied the effluent quality and removal efficiencies. Results indicated that reduced amounts of ammonia concentrations had increased removal efficiencies and the chemical oxygen demand (COD) concentrations responded the same. The increased removal efficiencies also occurred during a retention time of 10 days. They suggested that secondary

treatment of wastewater would provide optimal nutrients for duckweed production. Whitehead et al. (1987) suggested increasing cropping intensity in proportion to the nutrient loading rate to maximize removal rates. Research has indicated that the management of nutrient loading rates does affect the removal efficiency by duckweed.

Duckweed as a Potential Protein Supplement

Feed costs are a major portion of the annual cost of production in all livestock enterprises. The crude protein in most swine diets is its most expensive component. Crude protein provides essential elements necessary for superior growth and feed efficiency. The aquatic plant, duckweed, removes inorganic nutrients from wastewater; therefore, the plants have high nutritive values. Duckweed has been proven comparable to traditional feedstuff. The nutritional value of duckweed comes from the non-structural metabolically active makeup of the plant. The nutrient content of duckweed has been proven comparable to alfalfa and soybean meal. Traux et al. (1972) reported that duckweed was higher in protein and fat than alfalfa. The metabolizable energy of the duckweed was 1.96 kCal. /gram compared to the 1.65 kCal./gram of alfalfa. The experiment showed duckweed to be a favorable substitute for alfalfa in poultry diets. Haustein et al. (1992) conducted an experiment feeding broiler chicks. The experiment showed *Lemna gibba* had 380 grams of protein per kilogram after being dried. The results indicated that, as the level of duckweed increased, the

feed consumption and weight gain decreased. The reason for the decreased growth was believed to be due to the lowered metabolizable energy content of the *Lemna gibba* in the diet. The metabolizable energy is an important component in the growth patterns of livestock. Culley and Epps (1973) conducted a study to compare the nutrient value of various duckweed species. The mixed duckweed strands of the *Wolffia* and *Lemna* species had the larger nutrient value with a crude protein of 25.9% grown in freshwater lakes. The *Spirodela* species had the lowest nutrient value with a crude protein of 7.4%.

The potential protein value of duckweed depends on the composition of waste used as the growth medium. Culley and Epps (1973) reported that crude protein of duckweed from the swine waste lagoon reached as high as 40%. In this particular study, the 40% crude protein was comparable to soybean meal with a crude protein of 42%. The fat content of the same mixed duckweed strand was 5.8%, whereas the soybean meal was only 3.5%. Data from this experiment estimated duckweed grown on waters with high concentrations of swine wastes could yield up to 453,600 grams of dry duckweed per month per acre. A study by Hillman and Culley (1978) cites a duckweed with a crude protein of 44.7% grown on swine waste lagoons. When compared to soybean (dry seed) and dry cottonseed, the duckweed outperformed the alternative feedstuff. Hillman and Culley also believed those duckweed values closely related to alfalfa because they are not seed crops and are harvested to the same end point. The comparable value for alfalfa leaf meal was 20% crude protein. However, seed

crops such as soybeans and cottonseed meal had crude proteins of 37% and 41%. Another study by Patni and Atival (1989) focused on duckweed as a feed supplement. They found that the nutritional quality of duckweed to be satisfactory. The quality was comparable to wilted alfalfa silage. The digestibility of the protein was noted to range between 40% and 60%. Similar results were observed by Oron et al. (1985). This experiment also reported crude protein values of 49.4% in the highest concentrations of COD and ammonium. The average crude protein ranged from 30% to 45%. A protein concentration was obtained in this study from fresh duckweed. The crude protein of the fresh duckweed was 38.3% compared to the 32.4% crude protein in sun-dried duckweed. Lawson et al. (1974) conducted research on the methods of drying duckweed. The study indicated that drying methods can affect the crude protein of the duckweed. Oven-dried duckweed proved to have the best crude protein recovery, but was cost prohibitive due to the large amounts of duckweed harvested. Sun drying was the most cost-effective method for drying duckweed.

Duckweed contains a wide array of amino acids. Amino acid requirements are essential to non-ruminants. Swine do not have the ability to synthesize certain amino acids that are essential to in their diets. Therefore, the amino acid concentrations of the nutritional swine diets are extremely important. Leng et al. (1995) reported that pigs can use duckweed as a protein and energy source with slightly less efficiency than soybean meal. The amino acid profile of duckweed proves favorable to traditional harvested crops. The nutritive value of

the protein depends greatly on the amino acid constituents. Dewanji (1993) reported that the amino acid content of the protein showed a small variation compared to the variation in actual crude protein. The leaf protein remained uniform. Dewanji also suggested through in-vitro studies using pepsin and pancreatic fluids that the aquatic leaf proteins have digestibilities of 70%. Skillicorn et al. (1993) reported that, as the concentration of protein in duckweed increases, the important amino acids such as lysine and methionine will increase as well. Johnson et al. (1998) observed a 1.13% lysine content in duckweed. That value is half of the lysine content of 2.63% in soybean meal (NRC, 1998). Rusoff et al. (1980) noted a small variation in amino acid composition among four various duckweed species.

Conclusion

Feed represents up to approximately 70% of the total cost of a swine operation. The crude protein supplementation in the rations represents the majority of the total feed costs. Soybean meal is commonly used as the main crude protein supplement. Any method to produce a least-cost ration will help increase the operation's profits. Duckweed is one option to decrease the cost of supplementation in swine rations. The nutritional quality of duckweed is comparable to soybean meal and cottonseed meal. The nutritive value greatly depends on species selection and the overall management regime. Duckweed requires intensive management to obtain maximum results. The performance of

pigs on the duckweed rations would determine the operation's capability to produce its own protein source. The integrated production system also must be economical to the operation's overall profits. Both the economics and the pig's performance will determine the feasibility of a duckweed production system.

Research was conducted to determine if a swine production system can successfully utilize the harvested duckweed as a crude protein supplement for animals. One objective of this research is to determine the economical approach of a wastewater treatment facility growing duckweed for use in a concentrated animal feeding operation. A hypothetical waste treatment system incorporating the production of duckweed will be designed and the estimated costs to install the system will be included. The second objective will determine the effectiveness of duckweed in swine diets. A feeding trial and a digestion trial will determine the growth performance and nutrient retention of duckweed. The trials will replace soybean meal with duckweed at various increments as the crude protein supplement. The results of this research will determine if duckweed can be an economical and a valuable crude protein supplement for swine.

Table 1.1. Waste Characteristics of Growing/Finishing Swine.

Component	Units	Grower 88 to 485 kg.
Weight	Kg/day/2205 kg. ^a	139.77
Moisture	Kg/day/2205 kg.	198.41
Total Solids	Kg/day/2205 kg.	13.98
Volatile Solids	Kg/day/2205 kg.	11.90
Fixed Solids	Kg/day/2205 kg.	2.07
COD	Kg/day/2205 kg.	13.36
BOD ₅	Kg/day/2205 kg.	4.59
Nitrogen	Kg/day/2205 kg.	0.93
Phosphorus	Kg/day/2205 kg.	0.35
Potassium	Kg/day/2205 kg.	0.49

^a 2205 kilograms (1000 pounds) represents one swine animal unit (United States Department of Agriculture's Agricultural Waste Management Field Handbook, 1997).

CHAPTER II

EFFECTS OF REPLACING TYPICAL CRUDE PROTEIN WITH DUCKWEED ON THE GROWTH PERFORMANCE IN GROWING SWINE

Abstract

In the formulation of swine rations, protein or more specifically amino acids are critical to growth and performance. Soybean meal is the most widely used protein supplement that supplies needed amino acids, but is an expensive ingredient when added to rations. The aquatic plant duckweed has similar crude protein levels and contains essential amino acids like lysine, threonine, and tryptophan that needed in swine rations. Experiment 1 utilized sixty-four nursery pigs in a feeding trial to determine the effects of replacing soybean meal with duckweed as the crude protein supplement. The data from the 21-day growth trial indicated there was a significant increase ($P<0.05$) in average daily gains between the 40% and 60% replacement of soybean meal with duckweed treatments and the control treatment. No differences ($P<0.10$) in feed efficiency were indicated between the treatments. Duckweed treatments had a long-term effect on final slaughter weights with a significant increase ($P<0.025$). The growth performance data showed that duckweed added to the ration as a source of crude protein, had beneficial effects in terms of average daily gain and final slaughter weights.

Introduction

One of the most expensive costs to any livestock operation is feed. The feedstuffs included in livestock diets have direct effects on the cost of production. The protein component is a critical nutrient in swine rations. Protein is an expensive macro-nutrient. In the formulation of swine rations, amino acids supplied by protein play a key role. The main amino acid deficiencies in swine diets are lysine and methionine.

In all diet formulations, soybean meal (SBM) is the most widely used protein supplement. The amino acids present in SBM and the abundance of the feedstuff make it attractive as a universal protein source; however, soybean meal does raise the cost of the diet. Currently, the average cost of soybean meal is \$132. per ton. The aquatic plant duckweed can have similar crude protein levels and contains the essential amino acids needed in swine rations. Duckweed can contain crude protein as high as 40%. The objective of this experiment was to evaluate the differences between soybean meal and duckweed when used as a protein supplements.

Materials and Methods

A total of sixty-four weanling pigs were used in a 21-day growth trial. The average initial body weight was 9 kilograms and the average age was 4 weeks. The pigs were blocked by weight, equalized by sex, location, and treatment. Pigs were maintained in 1.2 x 3.1 m pens at the Texas Tech University Confinement Swine Nursery at New Deal. The pigs were allotted to one of four

locations within the barn. The nursery was environmentally regulated for the duration of the trial. A 3-day adjustment period took place for the slotted floor and commingling.

All pigs were fed a constant starter diet for days 0 through 10. The starter diet is shown in Table 2.1. Pigs were allowed ad libitum access to feed and water during the duration of experiment. The pigs were fed four experimental diets from days 11 through 32. Dietary treatments were based on the replacement level of the protein source, soybean meal. Treatments were (1-control) protein from 44% CP soybean meal, (2) 20% replacement of soybean meal with duckweed, (3) 40% replacement of soybean meal with duckweed, (4) 60% replacement of soybean meal with duckweed as the supplemental protein source. The percentage replacement of soybean meal with duckweed is indicated on a weight basis in Table 2.2. The diets were balanced for amino acids. The composition of diet ingredients is listed in Table 2.2.

Feed samples for each treatment were taken at the beginning of each week and stored in a freezer. All the feed samples were ground in a Wiley Mill through a 1 mm screen. Samples were analyzed for crude protein(Table 2.3), minerals of interest(Table 2.4), dry matter(Table 2.3), ash(Table 2.3), and amino acids(Table 2.5). The nitrogen in the feed was analyzed by the Kjeldahl procedure and crude protein was determined by multiplying the percent nitrogen by 6.25. The dry matter was determined by heating the sample at 100°C for 12

hours. After dry matters were taken, the same samples were heated in a furnace at 600°C to determine the ash content.

The pigs were weighed on day 0, day 11, and day 33 to determine the weight gain information. The amount of feed given to the pigs was recorded to determine feed efficiency. The pigs were observed each day as designated by the animal care and use protocol. After completion of the feeding trial, the pigs were moved to the grower/finishing phase. The pigs were slaughtered around 24 weeks of age and close to 104 kilograms in weight. Final weights were taken before slaughter to determine if duckweed had a long-term effect on performance.

The data were analyzed by the General Linear Models procedure using Statistical Analysis System (SAS). The average daily gains, feed efficiency, and final slaughter weights were calculated using the averages of each pen. Data was analyzed by a random block design. The data was also analyzed for a linear, quadratic, or cubic contrast.

Results and Discussion

The weight gains and feed efficiency are represented in Table 2.6. Pigs fed diets containing the duckweed showed to had the highest average daily gains and feed intake. The palatability and consumption of the diets containing duckweed as a replacement for soybean meal was good. The pigs showed no

signs of refusing the treatments and the overall consumption was higher for the duckweed treatments.

There was a highly significant difference ($P < 0.01$) between the 40% and 60% duckweed diets and the control diet for average daily gain. No differences ($P < 0.05$) in performance were observed between pigs fed the control diet and 20% duckweed diet. This indicated that the 20% replacement of soybean meal with duckweed was of no advantage; however, numerical average daily gains were higher than those on the control diet. Johnson (1998) reported ruminants had the opposite effect. The higher the level of duckweed in the diets, the average daily gains and feed efficiency decreased. Haustein et al. (1992) also reported that as the level of duckweed increased in the diets, the mean weight gain of the chicks decreased linearly. Leng et al. (1995) quoted work by Haustein et al. (1992) showing that as the *Lemna* meal in swine diets increased, the live weight of the pigs decreased. This might have been due to the fact that a low protein and high fiber duckweed was used in the experiment.

Feed efficiency was measured during this experiment. The poorest feed efficiency was seen in the 60% duckweed treatments. The highest feed efficiency was observed in the 40% duckweed treatments. There was no significant difference ($P < 0.10$) between the dietary treatments. The pigs on the duckweed treatments consumed more feed than the control treatment, as shown in Table 2.6. Haustein et al. (1992) reported no significant difference was observed in feed conversion by chickens. The numerical values for feed

conversion did indicate decreased values as the level of duckweed increased in the diets.

Weights were taken prior to slaughter to determine if the duckweed had any long-term effects on performance. The pigs performed the same as during the experiment. The highest average weights were observed in the pigs that had received the 60% duckweed treatment during the nursery phase. The mean final slaughter weights are shown in Table 2.7. There was a significant increase ($P < 0.025$) between the control treatment and the duckweed treatments.

Johnson (1998) reported no difference in the finished weights of cattle that were initially on the duckweed treatments. Haustein et al. (1992) reported that chickens initially fed duckweed and then changed back to the standard diet had a higher rate of gain than the chickens that received no duckweed.

Implications

The pigs on the duckweed diets exhibited higher average daily gains, final trial weights, and final slaughter weights. Feed efficiency was close to the expected values in the N.R.C. for Swine, but the pigs on the duckweed treatments required more feed per pound of gain than the control treatment. Duckweed proved to be palatable and increased intake during the experiment. The data indicates that duckweed can be used as a crude protein source in swine diets.

Table 2.1: Ingredients present in 10-day starter diet.

Ingredient	Amount (kilogram)
Ground Milo	2,842
Soybean Meal	1,323
Calcium	49
Dical	62
Salt	13
Swine vitamin	66
Whey	44
ASP-500	11

Table 2.2. Ingredients contained in the Treatment Diets (% Dry Matter).

Ingredient	Control	Percentage Duckweed		
		20%	40%	60%
Milo	59.90	59.80	58.75	57.78
Soybean Meal	35.95	28.76	21.57	14.38
Duckweed	0.00	7.19	14.38	21.57
Mineral premix	0.09	0.09	0.09	0.09
Tylan	0.20	0.20	0.20	0.20
Lysine	0.04	0.12	0.30	0.20
Dicalcium Phosphate	1.40	1.40	1.19	0.85
Limestone	1.40	1.22	1.10	1.05
Salt	0.30	0.30	0.30	0.30
Blood Meal	0.43	0.43	0.43	0.43
Vitamin premix ^a	0.30	0.50	1.70	3.15

^a Analysis of premix:

Crude Protein	25%
Lysine	3.15%
Crude Fat	13%
Crude Fiber	2%
Selenium	2 ppm
Zinc	1900 ppm
Zinc from AA Complex	250 ppm

Table 2.3. The Percentage of Crude Protein (CP), Dry Matter (DM), and Ash of all Treatments. (dry matter basis)

Treatment	CP, %	DM, %	Ash, %
Control	23.46	91.38	5.63
20% Duckweed	20.78	90.03	7.58
40% Duckweed	20.95	91.69	8.65
60% Duckweed	19.37	91.07	9.84

Table 2.4. Acid Detergent Fiber(ADF) and Natural Detergent Fiber(NDF) of Duckweed used in Dietary Treatments. (dry matter basis)

Item	ADF	NDF
Duckweed ^a	23.47	38.02

^a Duckweed source from Kyle, TX

Table 2.5. Minerals Present in Treatment Diets.

Mineral	Units	Control	Percent of Duckweed		
			20%	40%	60%
Nitrogen	%	3.75	3.32	3.35	3.10
Calcium	%	0.56	1.31	1.38	1.39
Phosphorus	%	0.64	0.86	0.81	0.69
Potassium	%	1.12	1.00	1.03	1.01
Magnesium	%	0.21	0.26	0.27	0.27
Manganese	PPM	31.35	44.92	53.11	68.56
Iron	PPM	173.70	616.83	824.88	1062.49
Copper	PPM	9.65	7.33	5.22	4.56
Zinc	PPM	34.66	34.30	32.47	29.82

Table 2.6. Amino Acid Concentrations in the Treatment Diets.^a

Amino Acid (AA)	Unit	Control Treatment	Duckweed ^b
Essential Aas			
Histidine	% MOL	2.62	1.84
Arginine	% MOL	5.75	4.21
Threonine	% MOL	4.94	6.16
Valine	% MOL	6.60	7.21
Methionine	% MOL	1.58	1.58
Isoleucine	% MOL	5.34	4.99
Leucine	% MOL	10.11	9.28
Phenylalanine	% MOL	4.97	4.88
Lysine	% MOL	5.83	5.67
Non-essential AAs			
Aspartic Acid	% MOL	6.44	9.76
Glutamic Acid	% MOL	13.06	11.29
Serine	% MOL	5.90	5.46
Glycine	% MOL	6.44	9.26
Alanine	% MOL	8.68	9.91
Proline	% MOL	7.63	5.88
Tyrosine	% MOL	2.95	2.31
Cysteine	% MOL	1.16	0.32

^a Amino Acid Analysis by the laboratory of University of Texas.

^b 1st dried batch of duckweed from Kyle, TX. (duckweed added to treatments)

Table 2.7. Effect of Soybean Meal Replacement with Duckweed on Growth Rate and Feed Efficiency in Experiment 1.

Item	Treatments				Contrast
	Control	20% Duckweed	40% Duckweed	60% Duckweed	
Number of pens	4	4	4	4	
Number of pigs/pen	4	4	4	4	
Initial weight, kg.	41.31	41.36	41.56	41.78	
Initial trial weight, kg.	54.08	53.77	52.60	53.86	
Final weight, kg.	87.83	95.37	98.88	100.09	
ADG, kg. ¹	1.61 ^a	1.98 ^{ab}	2.20 ^b	2.27 ^b	0.004 ^L
ADFI, kg.	12.17	13.91	15.39	17.55	
FE, % ²	7.60 ^a	7.06 ^a	7.02 ^a	7.75 ^a	0.099 ^a

¹ Rows with different letters differ P < 0.01

² Rows with different letters differ P < 0.20

^L Linear effect

^a Quadratic effect

Table 2.8. Final Performance of Pigs in Experiment 1 Prior to Slaughter.

Item	Treatments			
	Control	20% Duckweed	40% Duckweed	60% Duckweed
Number of pigs	16	15 ^a	16	16
Avg. age at slaughter	24 weeks	24 weeks	24 weeks	24 weeks
Avg. final weights, kg. ¹	463.9 ^a	497.1 ^b	497.8 ^b	504.4 ^b
				0.012 ^L

^a One pig died after completion of the nursery experiment

¹ Rows with different letter differ P < 0.025

^L Linear effect

CHAPTER III

THE UTILIZATION EFFECTS OF DUCKWEED
SUPPLEMENTATION ON DIGESTIBILITY OF DRY
MATTER AND NUTRIENTS

Abstract

The nutrients consumed by young animals are vital for growth and development. The aquatic plant duckweed contains high amounts of nutrients that are essential for animal growth. Experiment 2 utilized twelve nursery pigs in a metabolism trial to determine the digestibility of nutrients and dry matter (DM) of diets containing 0, 40%, or 60% duckweed. There was a significant difference ($P < 0.001$) in dry matter digestibility between the control treatments and the two duckweed treatments. A significant decrease ($P < 0.01$) was shown between the control treatments and duckweed treatments for apparent digestible crude protein. The data on apparent digestible phosphorus also indicated a significant decrease ($P < 0.05$) between control treatments and 40% and 60% duckweed treatments. There was no differences noted between duckweed treatments in digestible DM, apparent digestible crude protein, and apparent digestible phosphorus. The duckweed treatments performed adequately for growth performance; however, the treatments did not perform well in digestibility of key environmental nutrients. The digestibility and feed efficiency of duckweed was lower than the soybean meal control treatment.

Introduction

Nutrients and different feedstuff can vary in overall digestibility. Digestion is the processes involved in the conversion of feed into absorbable forms. The nutrients consumed by young animals is vital to their growth and development. The aquatic plant duckweed contains high amounts of nutrients that are essential for growth. Johnson (1998) reported that duckweed diets for sheep had a similar digestibility to cottonseed meal. In that same study, soybean meal had a 69.3% crude protein digestibility and the duckweed had a crude protein digestibility of 77.53%. The objectives of this experiment were to determine the dry matter digestibility, digestible crude protein, and digestible phosphorus of swine diets containing duckweed.

Materials and Methods

Twelve weanling pigs were used to evaluate difference in digestibility between treatment diets. The pigs had an average initial body weight of 8.15 kilograms and an average age of 4 weeks. The pigs were housed in 28 X 13 inch metabolism crates in an environmentally regulated room at 80 to 85°F at the Texas Tech Swine Research Center. The experiment was blocked by weight, treatment, location inside room, and location within blocks. Treatments were replicated four times in this experiment, with four pigs per dietary treatment.

The digestibility trial employed a 5-day period of adjustment to the diets and metabolism crates. The actual collection period began on day 6 and ended

on day 10. The pigs were fed 2.84 kilograms during the collection period. The daily treatment intake per pig was 0.57 kilograms, 0.23 kilograms at morning feeding and 0.34 kilograms at evening feeding. Daily feeding times also remained constant during the duration of the trial. Collection took place each morning prior to feeding. Water was provided ad libitum during entire experiment.

Daily fecal output was collected, weighed, and frozen. At the end of collection, a percentage of each daily sample was taken to represent a total aliquot of 227 grams or more of wet feces. The aliquots were then frozen before being placed in a freeze dryer. The freeze dryer was used to dry fecal aliquots at -05°C until a constant weight was obtained. After drying, the samples were ground using a Wiley Mill fit with a 1 mm screen. The samples were stored in the freezer until further analysis. Fecal samples were analyzed for crude protein, minerals, and dry matter.

Collection of urine occurred at the same time as fecal collection and was measured on a weight basis. Daily urine output containers had 10 ml of HCL added to acidify the urine. A 10% aliquot was removed each day and then stored in glass bottles. At the end of the collection period, samples were thoroughly mixed and a 500 ml aliquot was removed and stored in a freezer. The fecal and urine samples were analyzed for nitrogen using the Kjeldahl procedure. Dry matters were also taken on the fecal samples. The dry matter was determined by heating the sample at 100°C for twelve hours.

The minerals present in the feed and feces were determined using a Thermo Jarrell Ash/Trace Scan machine. The samples were digested using a nitric acid and hydrogen peroxide acid wash(Jones and Case, 1990). A total of 0.5 grams of sample was taken in duplicate for digestion. The samples were allowed to sit overnight in 5 ml of nitric acid. The next day, the samples were heated to 125°C until no fumes were present. The samples were cooled and 1 ml of hydrogen peroxide was added and heated to the same temperature. This procedure was repeated until the digest was clear or until no color changes appeared. The sample were brought up to 50 mls with ultra pure distilled water at a 1:50 dilution factor for analysis by the Thermo Jarrell Ash/Trace Scan unit.

The laboratory data were analyzed by the General Linear Models procedure in SAS. The weight gains, feed efficiencies, digestible dry matters, digestible crude proteins, and digestible phosphorus values for each animal were used to analyze effects of treatment. The experiment was designed and the data was analyzed using a random block design.

Results and Discussion

The performance results of Experiment 2 are represented in Table 4.1. The average digestibility of nutrients among treatments is presented in Table 4.2. Pigs #1 and #10 on the control treatments became sick during the trial and did not consume the treatment well. The rest of the pigs had excellent consumption

of all treatments. A higher fecal output was visually observed for the pigs on the duckweed treatments.

The performance data indicated higher average daily gains for the control treatment. There was no significant difference ($P < 0.10$) between dietary treatments or location within the metabolism room for the duration of the experiment. A difference in room location was observed for days 5 to 10. The feed efficiency for days 0 through 10 was the lowest at 2.71 pounds for the 40% duckweed treatments; however, the highest average daily gain of 0.59 pounds was observed for the control treatment. There was a significant difference of ($P < 0.04$) between the control treatment and the 40% duckweed treatment, but there was no significant difference between the control treatments and the 60% duckweed treatments.

Digestibility of dry matter for each animal is represented in Table 4.3. The highest dry matter digestibility also occurred in the control treatment. There was significant decrease ($P < 0.001$) between the control treatments and the duckweed treatments. The mean digestible dry matter was 94% for the control group; whereas, the 60% duckweed group's digestible dry matter was 81%. There was no significant difference ($P < 0.10$) between the duckweed treatments.

Digestibility of Key Environmental Nutrients

The retention of important nutrients such as nitrogen and phosphorus is important from an environmental standpoint. Nutrient contamination in groundwater is a particular concern for health and environmental quality. Groundwater is a major source of drinking water and therefore must be protected. Nitrogen runoff and leaching can affect groundwater creating high nitrate levels that are harmful to humans. Phosphorus runoff is often associated with high concentrations in surface waters that result in eutrophication. These are two examples of effects that nutrients have on health and the environment. The absorption of nutrients by the digestive track has three general functions. Nutrients are responsible for maintaining body structure, providing an energy source, and regulating functions in the animal's body. The absorption of nutrients by non-ruminants takes place in the small intestines and then, through active transport and passive diffusion, enters the blood and lymph systems. It is impossible to determine exactly how much phosphorus was digested due to the absorption within the body. Many minerals and other vitamins affect phosphorus absorption in the animal's body. This experiment simply was designed to determine the amount of phosphorus and nitrogen present in the manure that may, or may not, pose a threat to the environment.

The apparent digestibility of crude protein in Table 4.2 was similar to the digestible dry matter. The mean apparent digestibility of crude protein for the control treatments was 91.67 % and 80.26 % for the 60 % duckweed treatments.

There was a significant decrease ($P < 0.01$) between the control treatments and the duckweed treatments; however, there was no significant difference between the duckweed treatments.

The mean apparent digestibility of phosphorus in Table 4.2 reports that the control treatments was 77% and 66% for the 60% duckweed treatments. There was a significant decrease of ($P < 0.05$) between the control treatments and the 60% duckweed treatments. There was also no significant difference between the duckweed treatments.

Implications

The nursery pigs on the 40% and 60% duckweed treatments had lower digestible dry matters, apparent digestibility of crude protein, and apparent digestibility of phosphorus. The feed efficiency for the same group of nursery pigs indicated the opposite effect. The poorest feed efficiency was present in the 40% duckweed treatments. The duckweed treatments performed adequately for growth performance; however, the treatments did not perform well in digestibility of key environmental nutrients. The low nutrient digestibility of the duckweed diets can increase the need for an advanced wastewater treatment system. An advanced wastewater treatment system's goal is to remove nutrients from wastewater. The proposed duckweed production system can take care of the increased nutrient excretion. The increased growth performance along with the

advanced treatment system together makes duckweed an attractive feed supplement for an integrated swine operation.

Table 3.1. Effect of Soybean Meal Replacement with Duckweed on Growth Rate and Feed Efficiency in Experiment 2.

Item	Treatments		
	Control	40% Duckweed	60% Duckweed
Day 0 to 5			
ADG, kg. ¹	1.23 ^a	0.88 ^a	0.88 ^a
ADFI, kg.	2.54	2.95	2.80
FE	2.06	3.38	3.16
Gain, kg.	6.15	4.37	4.11
day 5 to 10			
ADG, kg. ¹	1.34 ^a	1.23 ^a	1.23 ^a
ADFI, kg.	2.76	2.76	2.76
FE	2.04	2.24	2.22
Gain, kg.	6.75	6.15	6.19
day 0 to 10			
ADG, kg. ¹	1.30 ^a	1.06 ^a	1.06 ^a
ADFI, lb.	2.65	2.84	2.78
FE ²	2.05 ^a	2.71 ^b	2.62 ^{ab}
Gain, lb.	12.90	10.52	10.63

¹ Rows with different letters differ P <0.05

² Rows with different letters differ P <0.08

Table 3.2. Digestible Dry Matter(DM), Digestible Crude Protein (CP), and Digestible Phosphorus.

Metabolism Crate	% Digestibility of DM ¹	% Apparent Digestibility of CP ¹	% Apparent Digestibility of Phosphorus ¹
Control Treatment			
Crate 1	94.82	92.55	78.33
Crate 4	92.36	90.41	74.01
Crate 9	93.15	89.76	74.25
Crate 10	95.46	93.95	82.31
Averages	93.95 ^a	91.67 ^a	77.23 ^a
40% DW Treatment			
Crate 3	87.75	87.87	71.97
Crate 6	78.07	74.96	62.06
Crate 7	83.51	80.56	68.99
Crate 12	85.80	83.77	72.83
Averages	83.78 ^b	81.79 ^b	68.96 ^{ab}
60% DW Treatment			
Crate 2	82.90	81.04	67.48
Crate 5	83.22	82.33	69.98
Crate 8	75.49	74.73	52.72
Crate 11	83.67	82.93	62.13
Averages	81.32 ^b	80.26 ^b	63.08 ^b

¹ Rows with different letters differ P < 0.05

CHAPTER IV

THE ECONOMIC IMPACT OF A WASTEWATER TREATMENT SYSTEM INCORPORATING THE PRODUCTION OF DUCKWEED

Introduction

Water is an essentially predominant nutrient that plays a major role in supporting all life, and is becoming a limited resource in many regions. In recent years, water conservation and reuse has become increasingly important. Crops have an essential need for water and nutrients for growth and yield. The need for irrigation water for crops has increased, due to the depletion of the Southern High Plain's Ogallala Aquifer. The reuse of wastewater for irrigation can reduce the stress on natural water sources.

The scarce and valuable water supply is protected under the Clean Water Act of 1972. The Clean Water Action Plan ensures water quality standards. Agriculture is believed to be a contributing source of non-point pollution to surface and groundwaters. Alternate water sources are needed to sustain the rapid growth of intensive livestock production. Those alternative sources can be achieved by integrated wastewater treatment technologies.

Wastewater treatment was designed to ensure the protection of the environment and human health. The purpose of wastewater treatment is to remove organic materials, nutrients, heavy metals, and disease-causing

organisms. A major concern of wastewater management is the effect on water quality. Poor wastewater management can cause water pollution, soil pollution, and odors. The animal industry on the Southern High Plains produces more manure than can be applied to the available cropland without environmental pollution. CAFOs use large volumes of water for animal consumption and manure management. The nutrient concentrations in wastewater are a valuable source of plant nutrients for crop production. The traditional land application of manure has limitations. Manure application rates should be limited to concentrations that are required by the crop. Excessive application of manure can lead to pollution. Groundwater pollutants, such as nitrogen and phosphorus, associated with wastewater are nutrients that are quickly absorbed by the soil profile. Crops can only use so much manure as a fertilizer source. Another outlet for manure utilization must be examined to efficiently decrease environmental problems.

The main goal for concentrated animal feeding operations is to adopt an environmental plan that is profitable and beneficial to the industry. Livestock operations strive to maximize production efficiencies and decrease pollution within the current production system. An integrated wastewater management system is one way to achieve such goals. The objectives of an integrated wastewater treatment system are to collect, store, and utilize the manure to prevent environmental pollution. The benefits and costs of an integrated wastewater system are major determinants in the selection of treatment systems.

The objective of this research is to determine if a duckweed system can be economically installed as a wastewater treatment system for a swine confinement operation. Duckweed utilizes wastewater to produce a valuable end product. The aquatic plant is an attractive feed ingredient. The costs and design considerations associated with a waste treatment system are important to the livestock production industry. The costs of production must remain low to be profitable. The components of a manure management system contribute to the production costs. The duckweed production system was chosen due to its removal rates and nutritional benefits. Duckweed has been proven as an attractive feed ingredient for ruminants and non-ruminants. Another important benefit is the quality of water present after the high removal rates of nutrients and dissolved solids by duckweed. A hypothetical waste treatment system will be designed for a swine operation to determine the investment costs to incorporate a duckweed production system.

Wastewater Treatment System

A system was selected to utilize natural responses to achieve high rates of treatment. The primary natural components used are anaerobic conditions, aerobic conditions, and aquatic plants. Primary treatment is achieved by a settling tank and a liquid/solid separator. The goal of primary treatment is to remove solids. Secondary treatment is achieved by the Integrated Facultative Pond (IFP). The integrated system employs a combination of natural anaerobic

and aerobic conditions. The goal of secondary treatment is to remove the BOD. To further remove nutrients and dissolved materials in an advanced treatment process, aquatic plants are used. Duckweed plants are capable of removing nutrients and dissolved solids present in wastewater. The duckweed ponds are designed for maximum production. The plants can be substituted or added to the production diets as the crude protein source. The design layout of the waste treatment system and production of duckweed is shown in Figure 2.1. Each treatment component is explained in future sections.

Swine Operation

A hypothetical swine operation was used to estimate the cost of implementing a waste treatment system producing duckweed. Some general assumptions were made as to the production system and facilities. The assumptions are based on a grower/finisher swine operation.

The production system used in the grower/finisher operation plays a key role in developing the waste treatment facility. A total confinement operation has been selected to represent the industry standards. Four confinement units (buildings) will be used to house 950 pigs in each unit. The operation will have a one-time capacity of 3800 pigs. The average number of litters per year is 2.3 for a reproductive sow. With this in mind, the operation will produce 8740 pigs per year.

The layout of the facilities also plays a role in selecting a waste treatment system. The confinement units will be totally enclosed to regulate the production environment. The pigs will be housed on slatted flooring allowing for collection of waste in tanks below the floors. The collected waste is flushed to a storage tank twice per day to reduce ammonia concentrations within the units. The total volume of flush water needed each day is 15 gallons per head or 57,000 gallons per day. The waste treatment plan allows for 75% of the 57,000 gallons per day to be recycled back into the units for flushing. These specific plans help reduce the need for fresh water, which may or may not be a limiting factor. The daily manure production of growing/finishing swine is 0.18 cubic feet per day. The total flow to the storage tank will be approximately 62,000 gallons per day. These specific assumptions determined the treatment system selected and the design considerations of that system.

Storage Tank

A storage tank will be used to collect waste prior to pond treatment. The waste will flow by gravity to a concrete storage tank (see Figure 2.2). The storage tank volume requirement will be 125,000 cubic feet with a 15-day storage capacity. The increased storage capacity will create a safety feature in case of unforeseen problems in the waste treatment system. This is sufficient time to allow for fermentation in pit of the integrated facultative pond (IFP). The tank will be a square cast-in-place concrete structure placed in the ground. The solids will

be given time to settle to the bottom of the tank and the wastewater from the top will be recycled once per day to flush the swine units. A pump will send the solids and wastewater from the bottom of the tank to a liquid/solid separator before entering the IFP pit.

Liquid/Solid Separation System

A liquid/solid separator will be used in this system to reduce the amount of sludge entering the IFP. The idea of solid separation has many advantages. A reduction in the BOD is achieved by separation, thus creating higher removal efficiencies by the treatment pond. The reduced amount of solids entering the pit will in turn reduce the residence time inside the pit. The solids collected by the separator can be economically used as a fertilizer source for surrounding crops. The liquid/solid separator unit uses the force of gravity to allow the solids to be pushed down to a concrete collection box. The separator unit and collection area should be covered to prevent runoff. The liquid will be collected through the slots of the screen and will be pumped to the IFP. The stationary system must be cleaned by hand each day or on a regular basis to keep the system running at maximum efficiently.

Integrated Facultative Pond

Waste treatment ponds have been widely used in the United States to treat all types of wastewater. Pond systems depend on the type of biological

reactions needed for waste treatment. The facultative, aerated, aerobic, and anaerobic ponds are the most commonly used natural wastewater treatment systems. There are disadvantages and advantages to each ponding system. Facultative and anaerobic ponds yield high BOD removal, but do produce an odor. The aerobic and aerated ponds also provide high removal rates, but sludge buildup is associated with these ponds. A major amount of nutrient removal takes place during this stage. Ammonia is the main form of nitrogen leaving the IFP. In aerobic conditions the process of nitrification will break down ammonia to nitrite to nitrate to molecular nitrogen. Sweeten (1994) reported that ammonium was the primary form of nitrogen from dairy wastewater supernatant leaving the anaerobic primary lagoon. The Advanced Integrated Wastewater Pond Systems(AIWPS), designed by Oswald (1990), incorporates biological environments to achieve high rates of treatment. The AIWPS uses a series of ponds to create an easily maintained, reliable, and cost effective means to treat municipal wastewater. An adaptation of the AIWPS is the Integrated Facultative Pond(IFP). The IFP uses a combination of anaerobic fermentation and aerobic conditions producing bacteria for waste removal. Advantages to the IFP are less land area, reduced odors, and reduced amounts of, if any, sludge accumulations.

This system was chosen for its treatment and economical advantages. The IFP system integrates a fermentation pit and an aerobic outer pond into one unit(see Figure 2.3). Primary and secondary treatment can be achieved in the IFP. The fermentation pit is submerged to create anaerobic conditions. Solids

go through sedimentation and fermentation to the point where ash is the only thing remaining in the pit. The pit is designed to meet a flow rate of 19,400 gallons per day. The upflow velocity inside the pit must be less than 2 feet per day to allow for solid deposition. This allows for solids to remain in the pit for fermentation. Another design consideration is that the area of the pit should not exceed 0.25 acres to prevent excess natural mixing from occurring inside the pit. This limitation prevents mixing of surface water with the anaerobic water within the pit. The residence time within the pit is approximately 4 days. This retention time increases the volume inside the pit. A pit volume of 316,000 cubic feet is needed to sustain the upflow velocity. The area needed for the pit would be 0.48 acres. To account for the large pit volume, the pit will be divided in half. A liner will be used to divide the pit. Each side will have a maximum volume of 159,000 cubic feet. The surface area of each side will be 0.24 acres. This procedure will prevent mixing from occurring inside the pit. The final product inside the pit is in a biodegradable form that overflows into the outer pond.

The next stage in the IFP would be the overflow from the pit to the shallow aerobic pond (see Figure 2.3). The dissolved oxygen present in the shallow pond encourages algae growth on the water's surface. The mixing allows exposure of all algae to sunlight. The photosynthesis, aeration, and bacteria provide oxygen to break down nutrients and total suspended solids. The detention time within the aerobic pond is usually less than 30 days. The shallow depth also provides odor control, which has become increasingly important in

swine operations. The volume in the outer pond in the southern region should be 15 times the volume of the pit. Therefore, the outer pond volume needs to be 4,800,000 cubic feet. A depth of 10 feet is needed in the outer pond to sustain the overflow from the pit. The total area of the IFP would be 13 acres.

Duckweed Ponds

The duckweed ponds were designed using some basic assumptions. The average amount of nitrogen produced by a pig is 0.42 pounds per animal unit per day. A total of 3800 pigs will supply nitrogen to the duckweed ponds at any given time. According to Fedler (1998), an estimated figure of 150 pigs will supply enough nitrogen for one acre of duckweed production. With this value in mind, a total of 25 acres is needed for duckweed production.

The design criteria for the duckweed ponds are to maximize growth with limited amounts of labor. The ponds were designed in a series to account for flow and retention time. Each series will contain five ponds to equal a 5-day retention period. Each individual pond will be 1245 feet in length, 35 feet in width, and 18 inches in depth. A 35-foot width was chosen as a maximum width to sufficiently circulate the wastewater and duckweed uniformly. The circulation will be achieved using a regenerative blower and air-lift pumps. This method will provide ease of harvesting the duckweed and aeration of the pond. An estimated total of 12 air-lift pumps and a one horsepower regenerative blower will move the water throughout the pond. The vertical riser will be 15 inches below the water

surface. Parker and Suttle (1987) indicated by a logarithmic regression that an air-flow rate of 10 cubic feet per minute injected at 12 inches below the water surface would yield a flow rate of 30 gallons per minute through a 4 inch diameter pipe. Air can be supplied to air-lift pumps by regenerative blower pumps. Air-lift pumps are inexpensive and an effective method to circulate water in ponds. The total surface area of each pond is 1 acre. Each pond will have curved ends to enhance the movement of water (see Figure 2.5). The pond will have a fiberglass divider to keep the duckweed from gathering up in the middle of the pond, as is sometimes seen with circulation. The depth of 18 inches will allow the duckweed plants to obtain the adequate nutrients for growth. The depth can provide temperature buffering and detention time for wastes high in BOD.

The flow into the duckweed ponds will be achieved using gravity flow from the IFP. To evenly distribute wastewater to each series of duckweed ponds, an overflow box can be used. The box will use a float and polyvinyl chloride (PVC) pipes to move the wastewater by gravity flow. The height of the PVC pipes inside the box will be determined by the distance the wastewater must travel to reach the pond series. This method will create an even continuous flow of nutrients from the IFP. Each time wastewater is added to the duckweed pond, a float will allow a specific amount to be placed into the next pond in the series. The wastewater will remain in each pond for 1 day and in the series for 5 days. As previously indicated in the literature review, a 5-day retention period is optimal for growth and nutritive values.

Each duckweed pond will be covered to maximize production. The Southern High Plains region is susceptible to high winds on a daily basis. The duckweed plants must be protected from the wind. Without the use of covers, the duckweed would be blown onto the embankment. The larger the surface area of the pond the greater the wind velocity will be without covers. The pond covers will allow the duckweed to cover the surface area of the pond. The additional costs should be offset by increased production. The covered ponds will also shield the direct summer sunlight, which will stress the duckweed plant as the surface water temperature heats up faster than below the surface. The surface water temperature can be easily maintained by the covers.

The yield possibilities for this type of operation could amount to as much as 1,129,464 grams per month per acre, as estimated by Fedler (1998). Oron et al. (1987) reported a dry yield of 1736 grams per month per acre on a 12-inch deep pond. This low yield value reported by Oron et al. (1987) could be due to the small laboratory conditions used to grow the duckweed. Another particular study estimated duckweed grown on a swine lagoon would yield 6,350,400 grams per month per acre on a wet basis (Culley and Epps, 1973). The estimated dry yield based on a 95% moisture content would be 317,520 grams per month per acre. Duckweed yields will vary depending on seasons. The highest yields will be achieved during the summer months and early fall months. The amount of dry duckweed produced can be used to replace or add to the crude protein supplementation source in the diet.

The best method of harvest for this particular operation is not well defined. There are many possible harvesting methods. Duckweed plants are easily harvested because they float on the surface and because of the size of the plant. The plants could be collected by a conveyor belt that is placed at one end of the pond. A canal type of device can be used to collect and move the floating plants towards the harvesting conveyor belt. The belt could then move the plants into the harvest truck and be transported to the drying beds for sun drying. Another method of harvesting could be achieved by an auger system that collects the plants and feeds the plants on a harvest truck. Drying the duckweed, to remove the high amounts of moisture, should take approximately 2 days during dry climatic conditions. The plants should be turned periodically to allow them to dry quickly. Optimal drying conditions involve placing the harvested plants on screens to allow the air to circulate among the plants. Drying beds can be used to support the large production of duckweed in this system. Recommendations by Oron (1990) suggest that adjacent drying beds can be estimated by a ratio of 1:10. The proposed system would require 2 drying beds to sustain weekly duckweed harvesting. The elimination of drying can be achieved when the plant is fed to livestock wet. The wet plant can be fed alone or mixed in with other feedstuff. Rusoff et al. (1977) indicated that the species, *Spirodela polyrhiza* and *Spirodela oligorrhiza*, were palatable on a wet basis. Le thi Men et al. (1997) fed fresh duckweed ad libitum. The data indicated the *Lemna* species fed improved the reproductive performance of sows. The feeding of duckweed on a wet basis

could also reduce the amount of harvest management required in the operation. The weekly harvest rates of duckweed should be determined on a monthly basis by the operation's manager. Harvesting equipment can range from \$3000 to \$14,000 for duckweed production. The present harvesting equipment on the market is expensive and can sometimes only be used in large surface area ponds. Duckweed harvesting rates will vary according to production rates and climatic seasons.

Estimated Investment Costs

The economical feasibility of the wastewater treatment system and production of duckweed is important in the overall acceptance of the system. Few researchers have examined the costs of implementing duckweed production into livestock operations. The objective of this research was to determine if duckweed can be economically incorporated into a livestock wastewater treatment system. To accomplish this objective, many assumptions were made to estimate investment costs. A representative situation for wastewater treatment was designed based on a typical commercial growing and finishing swine operation. The estimated construction costs were obtained from the 1998 RS Means Manual for Heavy Construction. The costs were then adjusted to the Lubbock, Texas area in the Southern High Plains. The calculated costs were verified by personal communications with local professionals. Only the estimated investment costs are included in this assessment. The estimated economic

costs of the proposed wastewater treatment system with the production of duckweed is indicated in Table 4.1.

The assumptions made are representative to the Lubbock, Texas area. The initial investment costs will vary greatly due to the type of operation and treatment system. The following assumptions were made in estimating the costs included in Table 4.1.

- a. The selected land value is based on property that has adjacent water wells or the capability of a well to support the swine operation and the amount needed for wastewater treatment. The optimal location will also be next to cropland for possible land application purposes. The estimated value for such land will be \$750 per acre.
- b. The estimated expenses for pond construction are excavation at \$1.10 per cubic yard, soil compaction at \$0.10 per cubic yard, and liners for the pit at \$0.40 per square foot. The type of equipment selected to accomplish these jobs can greatly affect the construction costs.
- c. The piping requirements for the system include PVC pipe for sewage water distribution and a trenching system for the pipe. The estimated costs for 4-inch diameter PVC pipe is \$0.80 per foot and \$2.75 per foot for 8-inch diameter pipe. The estimated trenching costs will vary with excavation depth. The assumed average depth of 2 feet will cost an estimated \$1.95 per linear foot.

- d. The harvesting investment costs depend on the type and method selected for the operation. The conveyor belt method has an estimated cost of \$14,000. This particular method would require the a full-time employee to operate and move to each duckweed pond. The harvest system could be automated, but would require a larger initial investment costs. The full-time employee can easily maintain the entire waste management system, including harvesting. There are also less expensive methods to consider in harvesting duckweed plants.
- e. Manholes and catch basins are needed for the pumping system. Submersible pumps need a catch basin to work properly. The concrete construction at a 14-foot depth is estimated at \$7500 and \$3000 at a 6-foot depth.
- f. A contingency factor is placed in the table to account for differences in construction of ponds. An estimated factor of 20% should account for the differences.

Table 4.1 is the top of the line waste treatment system with the production of duckweed for use as a dried crude protein source in swine rations. The proposed system in Table 4.1 is rather costly in terms of investment costs. A least cost scenario is also included to demonstrate the differences in selection of components used in waste treatment systems. Table 4.2 indicates the estimated

investment costs for the least cost scenario. The scenario utilizes duckweed as a wet product and requires no additional costs for drying. It also uses a lower cost material to cover the duckweed ponds, which substantially reduces the total investment costs. The least cost scenario closely compares to the estimated investment costs of \$500,000 or \$130 per pig to build a confinement operation to sustain 3800 growing/finishing swine. The lower investment costs represented in Table 4.2 makes the duckweed system a more cost effective waste treatment system.

Impacts to Yearly Income and Expenses

It is necessary to put the estimated investment costs into prospective, some estimated costs and possible returns have been included on the operating expenses and income in a finishing swine operation. The replacement of soybean meal with duckweed as the crude protein source at different levels has been proved in Chapter II to improve average daily gains and final weight gains, but what are the economical benefits. The N.R.C. for Swine (1998) indicates that the average 331 kilogram pig would have an estimated feed intake of 2.58 kilograms per day. With this in mind, the hypothetical swine operation would need around 9,875 kilograms per day of feed to sustain 3,800 pigs. This translates into 11 tons of feed needed each day. An estimated milo finishing ration with soybean meal costs \$115 per ton. Soybean meal represents about 25% of the total ration cost.

The estimated yield production for the duckweed production system can be as high as 1134 kilograms per month or 37.65 kilograms per day on a dry basis. The average amount of soybean meal needed each day for the 11 tons of total finishing ration is 1497 kilograms. The amount of dried duckweed produced in this operation is simply not enough to supplement a grower/finishing swine unit; however, a nursery operation could utilize the duckweed produced at the given yield rate.

An average 10 kilogram nursery pig has an estimated feed intake of 0.46 kilograms per day. A total of 1.9 tons of starter ration is needed each day to sustain 3800 nursery pigs. An estimated milo based starter ration with soybean meal costs \$130 per ton. In this particular ration, the cost of soybean meal represents 38% of the total ration costs. The estimated yield production of 37.65 kilograms per day will provide enough duckweed for only a 15% replacement level. The 15% replacement of soybean meal with dried duckweed as the crude protein source only reduces the costs of soybean meal to 35% of the total ration costs. The overall difference in total ration costs is estimated at only \$4000 per year.

As one can see from this chapter, the treatment of wastewater outweighs the costs benefits in this particular operation. The integrated wastewater treatment system's goal is to utilize the manure produced in a productive manner. This system could utilize the duckweed to supplement a nursery swine unit. The research in Chapter II has demonstrated a beneficial effect on final

slaughter weight gain when duckweed was used as a partial replacement of soybean meal as the crude protein source. The increased final weights in the grower/finisher swine unit could influence the overall profits. The pigs will reach slaughter weight faster and less feed will be required, which will reduced the yearly feed costs.

Conclusion

The livestock industry is faced with the important decision of wastewater treatment. The additional costs of treatment can make some systems prohibitive. This research will provide information on one wastewater treatment system that produces two valuable end products. Those valuable end products are capabilities of water reuse and duckweed as a feed supplement. This research also utilizes the latest in advanced wastewater treatment using natural processes. The estimated investment values will be different for each operation, but this will provide livestock operations a general idea on the investment costs for incorporating the production of duckweed into the wastewater treatment system.

The estimated yield production of 1134 kilograms per month of dried duckweed each month can not sustain a grower/finisher swine operation, but will provide a level of replacement in a nursery unit. The amount of soybean meal needed to sustain 3800 finishing swine is 1497 kilograms per day. The amount of dried duckweed produced in this operation would not provide enough to

supplement a grower/finishing swine unit.

The average 10 kilogram nursery pig has an estimated feed intake of 0.46 kilograms per day. A total of 1.9 tons of starter ration is needed each day to sustain 3800 nursery pigs. The estimated yield production of 37.65 kilograms per day will provide enough duckweed for only a 15% replacement level. This 15% replacement of soybean meal with dried duckweed would create a combined effect on the level of operating costs needed to sustain a nursery swine operation and research indicated benefits of increased final slaughter weight gains.

Further research is needed in the areas of duckweed harvesting and drying to make it economical to produce. The harvesting and drying techniques estimated in this chapter were labor intensive, but can be done by one full-time employee. The use of duckweed as a wet product in diets should also be examined in the swine industry. This would lower duckweed production costs and could hopefully be used in the grower/finisher unit to lower feed costs. More research into the economics of livestock waste management can be used in the overall decision making process.

Table 4.1. Estimated Capital Investment Costs for Wastewater Treatment and the Production of Duckweed.

Item	Unit size	Cost per unit	Total estimated investment costs
Land			
Storage tank IFP	0.23 acres	\$750.00 / acre	\$ 172.50
Duckweed ponds	13 acres	\$750.00 / acre	\$ 9,750.00
Drying beds	30 acres	\$750.00 / acre	\$ 22,500.00
	2 acres	\$750.00 / acre	\$ 1500.00
Construction			
Storage tank	1 / unit	\$71,000.00 / unit	\$ 71,000.00
Separator IFP	1 / unit	\$27,450.00 / unit	\$ 27,450.00
pit excavation liner	11,680 yd ³	\$1.10 / yd ³	\$ 12,848.00
liner support	2,357 yd ²	\$3.60 / yd ²	\$ 8,485.20
outer pond	1 unit	\$1000.00 / unit	\$ 1000.00
Duckweed ponds	177,770 yd ³	\$0.10 / yd ³	\$ 17,777.00
ponds	60,538 yd ³	\$1.20 / yd ³	\$ 72,645.60
covers	121,076 yd ²	\$24.75 / yd ²	\$ 2,996,631.00
dividers	10,375 yd.	\$2.65 / yd	\$ 27,493.75
harvesting equipment	1 / unit	\$14,000.00	\$ 14,000.00
harvest truck	1 / unit	\$25,000.00 / unit	\$ 25,000.00
drying beds	9,680 yd ²	\$1.06 / yd ²	\$ 10,260.80
Piping			
4 inch diameter	3167 yd.	\$8.82 / yd	\$ 27,932.94
8 inch diameter	167 yd.	\$16.08 / yd	\$ 2,685.36
Contingency Factor	20%		
Totals			\$ 3,349,132.15

Table 4.2. Least Cost Scenario of Estimated Capital Investment Costs for Wastewater Treatment and the Production of Duckweed.

Item	Unit size	Cost per unit	Total estimated investment costs
Land			
Storage tank IFP	0.23 acres	\$750.00 / acre	\$ 172.50
	13 acres	\$750.00 / acre	\$ 9,750.00
Duckweed ponds	30 acres	\$750.00 / acre	\$ 22,500.00
Construction Costs			
Storage tank	1 / unit	\$71,000.00 / unit	\$ 71,000.00
Separator IFP	1 / unit	\$27,450.00 / unit	\$ 27,450.00
pit excavation	11,680 yd ³	\$1.10 / yd ³	\$ 12,848.00
Liner	2,357 yd ²	\$3.60 / yd ²	\$ 8,485.20
Liner support	1 unit	\$1000.00 / unit	\$ 1000.00
Outer pond	177,770 yd ³	\$0.10 / yd ³	\$ 17,777.00
Duckweed ponds			
Ponds	60,538 yd ³	\$1.20 / yd ³	\$ 72,645.60
Covers	121,076 yd ²	\$1.98 / yd ²	\$ 239,730.48
Dividers	10,375 yd.	\$2.65 / yd	\$ 27,493.75
Harvesting Equipment	1 / unit	\$14,000.00	\$ 14,000.00
Harvest truck	1 / unit	\$20,000.00 / unit	\$ 20,000.00
Piping			
4 inch diameter	3167 yd.	\$8.82 / yd	\$ 27,932.94
8 inch diameter	167 yd.	\$16.08 / yd	\$ 2,685.36
Contingency Factor	20%		
Totals			\$ 575,470.83

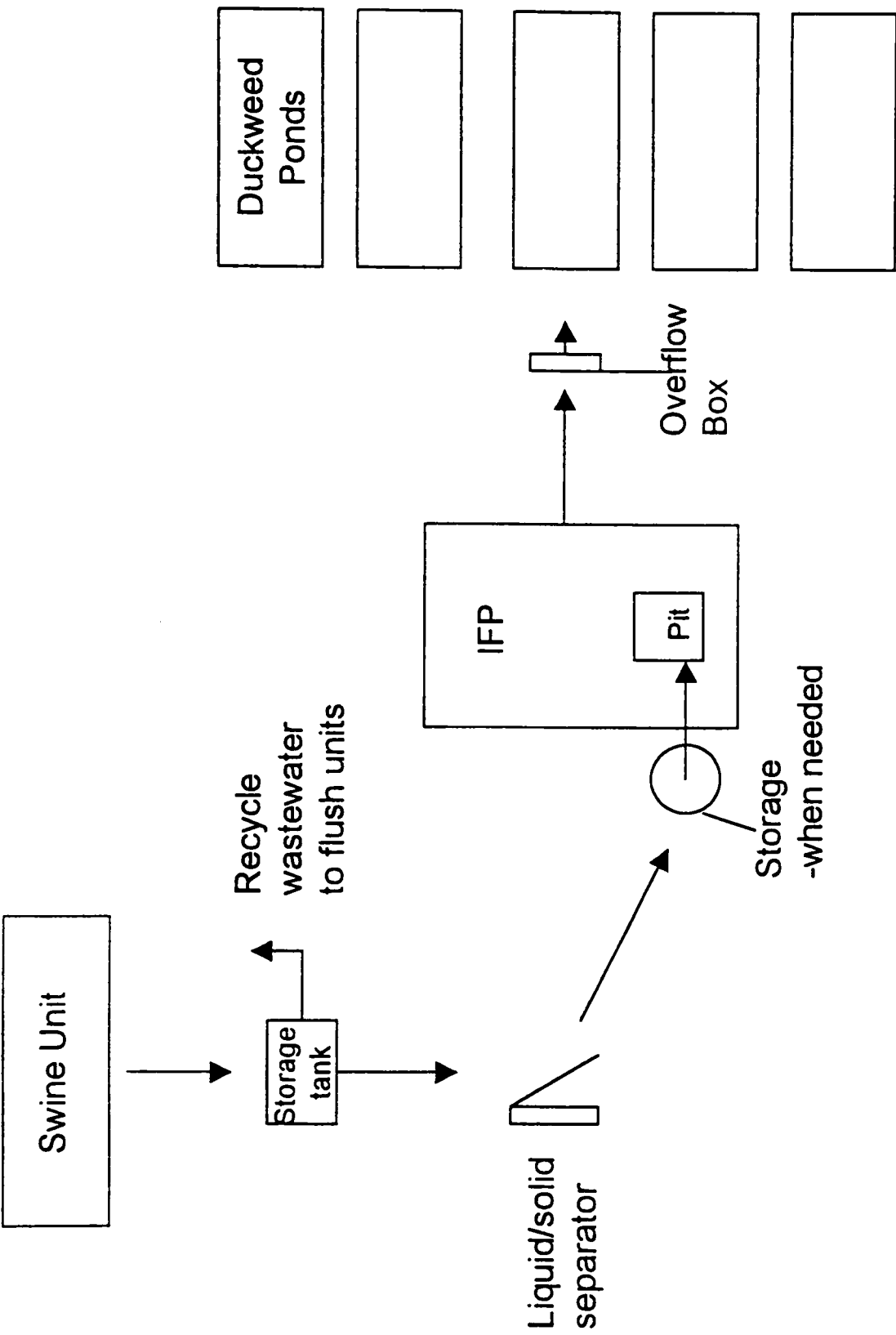


Figure 4.1. Design Layout of the Wastewater Treatment System with the Production of Duckweed

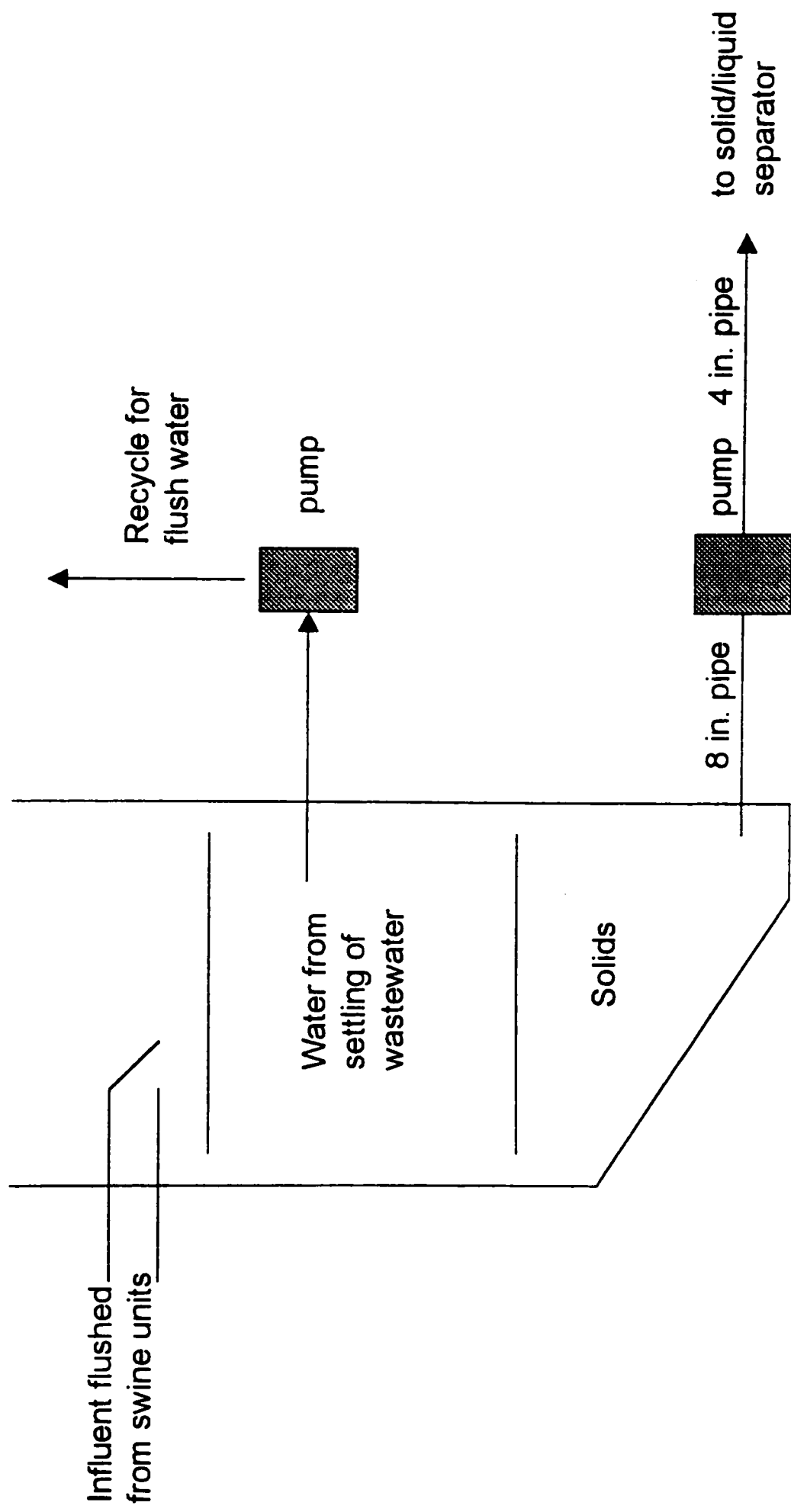


Figure 4.2. Design of Storage Tank

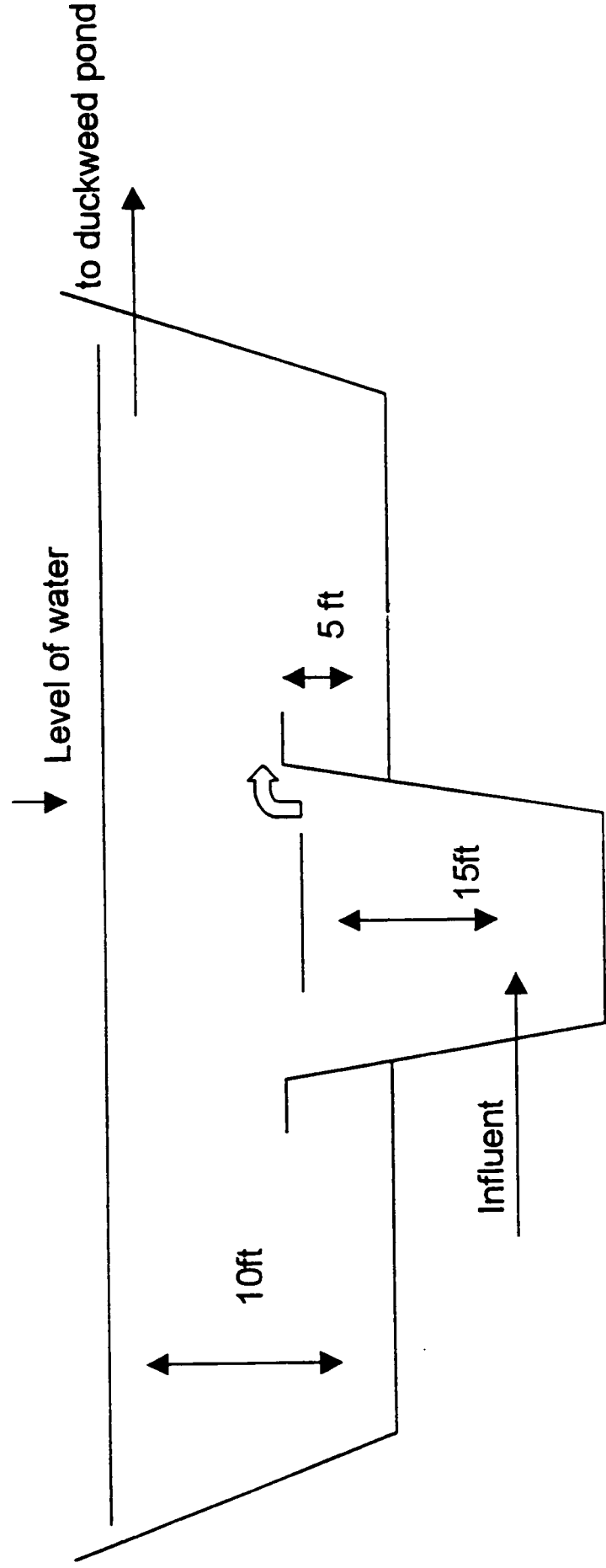


Figure 4.3. Side View of Integrated Facultative Pond.

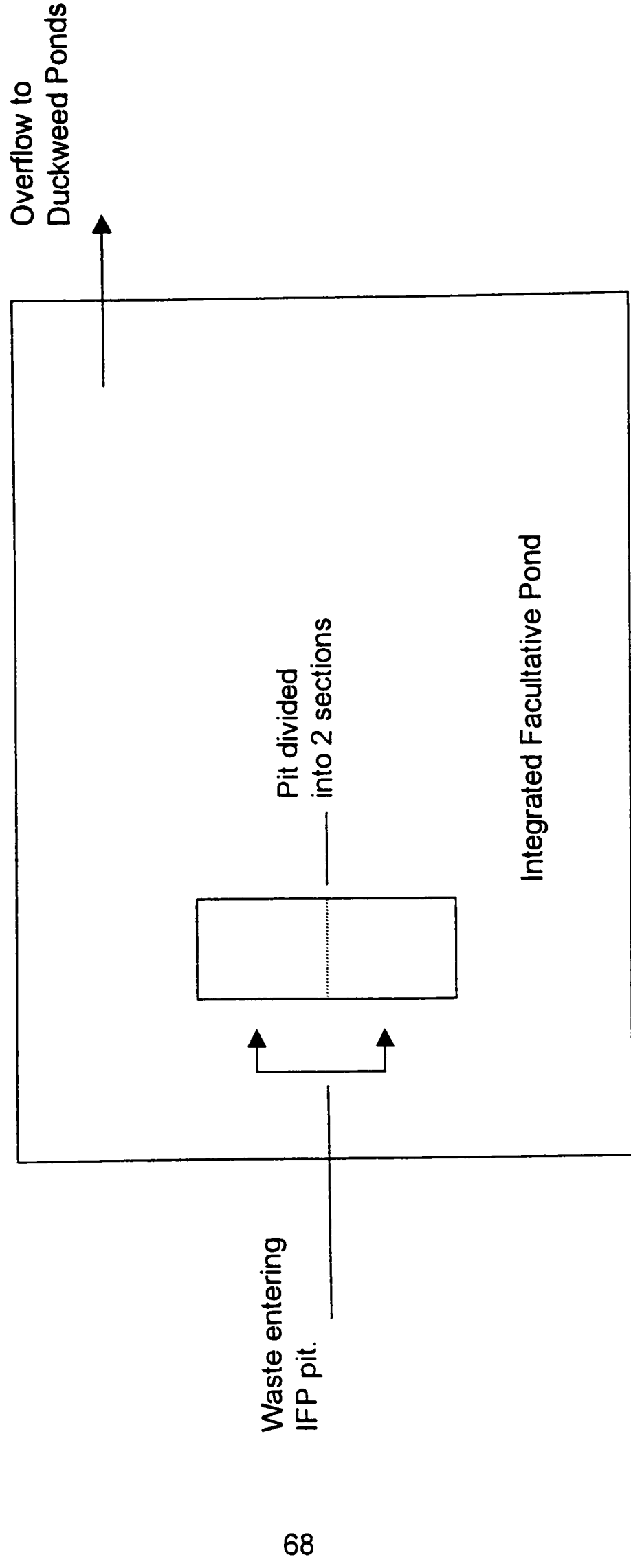


Figure 4.4. Top View of Integrated Facultative Pond.

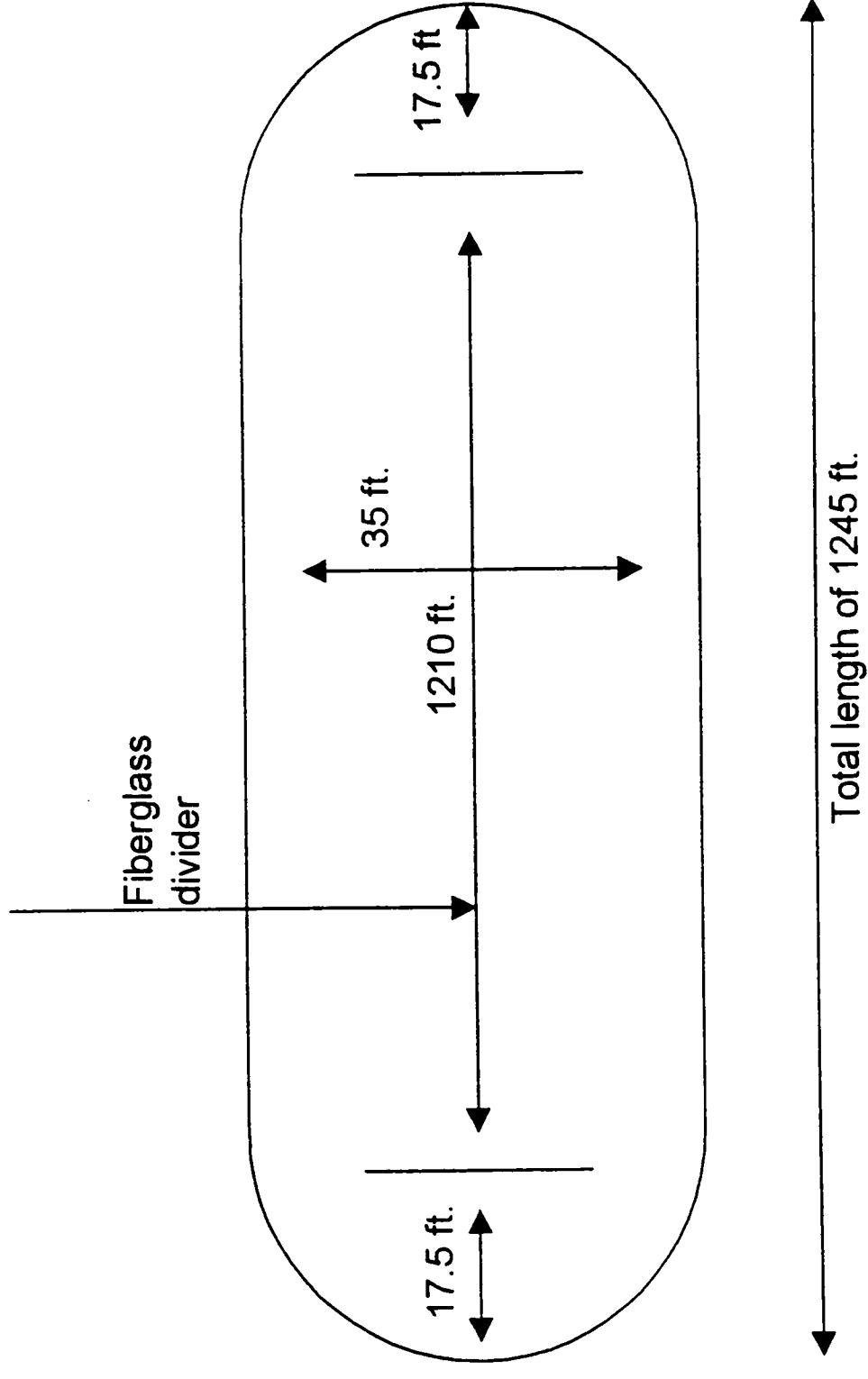


Figure 4.5. Single Duckweed Pond Design.

CHAPTER V

SUMMARY AND DISCUSSION

The recent target of environmental concerns has been animal feeding operations. The EPA states that agriculture contributes to the degradation of 60% of the nation's waters. A vast amount of change has been made in environmental regulations. Those regulations have forced agriculture researchers to look at wastewater management. The role of wastewater treatment is to provide an ample supply of fresh water to meet the demands of basic human and industrial needs. Aquatic plants can help provide the treated water needed for agricultural purposes and have become an integral part of the wastewater treatment process.

The aquatic plant, duckweed, removes nutrients and dissolved solids from wastewater. The high removal rates of nutrients can yield a high nutritive value. An integrated wastewater treatment system utilizes the natural treatment processes to produce a valuable end product. The objective of an integrated wastewater system is to collect, store, and utilize the manure produced to reduce the impact on the environment.

The livestock industry is faced with the important decision of wastewater treatment. The additional costs of treatment can make some systems prohibitive. The estimated investment values will be different for each operation, but this research provides livestock operators a general idea of investment costs for

incorporating the production of duckweed into a wastewater treatment system. An estimated capital investment of \$3 million is required for the treatment system with the latest in advanced technologies; however, the least cost alternative and most economical waste treatment system would require an estimated \$575,000 in investment costs. There are many investment options when incorporating the production of duckweed into a waste treatment system.

The estimated yield production for the duckweed production system can be as high as 1134 kilograms per month or 37.65 kilograms per day on a dry basis. The average amount of soybean meal needed each day for the 11 tons of total finishing ration is 1497 kilograms. The amount of dried duckweed produced in this operation is simply not enough to supplement a grower/finishing swine unit; however, a nursery operation could utilize the duckweed produced at the given yield rate.

An average 10-kilogram nursery pig has an approximate feed intake of 0.46 kilograms per day. A total of 1.9 tons of starter ration is needed each day to sustain 3800 nursery pigs. An estimated milo based starter ration with soybean meal costs \$130 per ton. In this particular ration, the cost of soybean meal represents 38% of the total ration costs. The estimated yield production of 37.65 kilograms per day will provide enough duckweed for a 15% replacement level. The 15% replacement of soybean meal with dried duckweed as the crude protein

source only reduces the costs of soybean meal to 35% of the total ration costs. The overall difference in total ration costs is estimated at only \$4000 per year.

The effectiveness of duckweed in swine diets will be a determinate of the proposed system. Research was conducted to determine the growth performance and nutrient digestibility of pigs fed diets containing duckweed as the crude protein supplement. The treatments replaced soybean meal at increments of 20%, 40%, and 60% of the protein source.

Duckweed proved to be palatable and increase intake during the experiment on growth performance. Nursery pigs on the duckweed treatments had the highest average daily gains, feed intakes, and final weight gains. Feed efficiency was the highest for the 60% duckweed treatment. Pigs also exhibited an added benefit of initial duckweed supplementation in final slaughter weights. The highest weights were seen in pigs that received the 60% duckweed treatments and the lowest weights came from pigs initially fed the control treatment. Duckweed proved to be an adequate replacement of soybean meal or in combination with soybean meal.

Experiment 2 used twelve weanling pigs to evaluate the digestibility of the duckweed treatments. The digestibility trial had a 5-day collection period to determine nutrient excretion. The dry matter digestibility of the control treatment was 93.93% and 81.32% for the 60% duckweed treatments. The average apparent crude protein digestibility of the control treatments was 91.67% and

80.26% for 60% duckweed treatments. Phosphorus exhibited the same results. The control treatments had an apparent digestibility of 77.23% and 66.08% for the 60% duckweed treatments. The growth performance of the pigs during the metabolism trial were similar to results of Experiment 1. Pigs on duckweed treatments had higher feed intakes and feed efficiencies; however, average daily gains were the highest for pigs on the control treatments. The pigs on duckweed treatments performed adequately for growth performance, but did not perform well in the digestibility of key nutrients. The low nutrient digestibility can be overcome by an advanced wastewater treatment system. The benefits in performance along with the proposed integrated treatment system make duckweed an attractive feed ingredient. The swine operation could also benefit from reduced operating expenses that will in turn increase their overall profit.

The research conducted was made on several assumptions as to the large scale production and installation of a duckweed treatment system. Further research is needed in the areas of duckweed harvesting and the use of duckweed as a crude protein source in a commercial size operation. The drying of duckweed for the feeding trials conducted in this research was not easy to achieve with the small number of screens compared to the large amount of wet duckweed. A commercial size operation would produce enough duckweed that it should be dried efficiently and quickly to prevent the duckweed from fermenting. There are many alternative methods of drying duckweed that are relatively inexpensive. Some alternatives can combine the harvesting and drying into one

step. This would reduce time required and cost to dry duckweed. Other uses of duckweed should be examined to eliminate the needed for drying duckweed.

Researchers should look into duckweed as a silage or a proper method of incorporating fresh duckweed into swine diets. The fresh/wet duckweed could be easily harvested and directly incorporated into swine diets. Further research is needed to determine the proper method of use in swine rations and the acceptance of the wet duckweed by the pigs.

The aquatic plant, duckweed, has been proved as an excellent remover of wastewater nutrients and has added growth performance benefits. The new and existing environmental regulations can be easily achieved by the incorporation of duckweed into a treatment system. The use of duckweed in combination with soybean meal can reduce the ration costs. These are all strong facts that support the use of duckweed as a feedstuff and important wastewater treatment component.

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