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Life cycle assessment (LCA) and techno-economic analysis (TEA) of various biosystems

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Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) of various biosystems

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DEDICATION

This thesis is dedicated to my parents, my husband, and the best gift in my life---- my son Austin. For their love, support and encouragement.

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NOMENCLATURE

d.b.	Dry Basis
DDGS	Distillers Dried Grains with Solubles
FCR	Feed Conversion Ratio
LCA	Life Cycle Assessment
NFT	Nutrient Film Technique
rpm	Revolutions per Minute
SD	Standard Deviation
TEA	Techno-Economic Analysis
w.b.	Wet Basis

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ABSTRACT

The fast-growing world population prompts researchers to evaluate both environmental and economic impacts during manufacture and service processing. Distillers dried grains with solubles (DDGS) fractionation and aquaponics are two bioprocesses aiming to make full use of materials and resources. This study conducted Life cycle assessment (LCA) and Techno-economic analysis (TEA) for DDGS fractionation and tilapia-basil aquaponics.

DDGS mainly contains protein, oil, fiber, and ash. DDGS could have more economic value and wider use if it could be separated into higher protein fraction and higher fiber fraction. In our work, the optimization of three parameters of a gravity separator (side slope, eccentric shaft vibration, and air flow rate), was conducted to separate DDGS. Based on the optimized results, LCA and TEA were conducted for DDGS fractionation for three scales.

Aquaponics is the system combining hydroponic and aquaculture, in which fish and plants are raised together and are beneficial from each other. LCA and TEA were conducted for a pilot scale of tilapia-basil aquaponics located on Iowa State University campus, and the results were scaled up to larger systems.

The results showed that when operation scale was large enough, both DDGS fractionation through a gravity separator and tilapia-basil aquaponics were profitable, and the environmental impacts decreased as the scale expanded. The results will provide useful data for optimizing DDGS fractionation and aquaponics.

CHAPTER 1

LITERATURE REVIEW

Abstract

In the 21st century, the continuous fast-growing population and limited natural resources require sustainable agriculture more than ever. How to add value to agricultural coproducts and how to improve profits within limited time and space have been explored by many agriculture researchers. Distillers dried grains with solubles (DDGS) fractionation and aquaponics are two bioprocesses aiming to make full use of materials and resources.

DDGS are co-products from corn ethanol fermentation. The main components of DDGS are protein, oil, fiber, and ash. There have been some researches focusing on various DDGS fractionations, which are ways aiming to acquire high protein and high fiber fractions to make more profits.

Aquaponics is a relatively new integrated system combining aquaculture and hydroponics. There have been some researches focusing on the mechanism and nutrient cycle, and economic feasibility of aquaponics operated in tropical areas.

Life cycle assessment (LCA) is an approach to evaluate the environmental impacts during a production or service. Techno-economic analysis (TEA) is a tool to evaluate economic potential based on technical information and assumptions. Both of them can help make decisions in pre-commercial stage and optimization in on-going operation.

This chapter focused on reviewing some common DDGS fractionation methods and some researches on aquaponics. This literature review provides the foundation for better understanding DDGS fractionation and aquaponics.

Keywords

Life cycle assessment (LCA), Techno-economic analysis (TEA), Distillers dried grains with solubles (DDGS), Fractionation, Aquaponics

1.1 Introduction

The world population reached up to 7 billion on Oct 31, 2011(UNNC, 2011), and it is still increasing at the rate of 2.5 person per second (USCB, 2014). In 2011, nonrenewable fossil fuels accounted for more than 80% of the United States' energy consumption (EIA, 2012). The fast-growing population not only requires more food and energy consumption to maintain life quality, it also brings heavy burden to the environment when releasing waste. As a result, how to develop sustainable agriculture, which aims to keep high efficiency during production and reduce environmental impact, has been exploring by many researchers. Distillers dried grains with solubles (DDGS) fractionation and aquaponics are two bioprocesses aiming to make full use of materials and resources. While DDGS fractionation adds value to manufacture coproduct, aquaponics improve profits within limited time and space. Both of the two processes are consistent with the concept of sustainable agriculture.

Life cycle assessment (LCA) is an approach to evaluate the environmental impacts during a production or service. Techno-economic analysis (TEA) is a tool to evaluate economic potential based on technical information and assumptions. Both of them are popular tools to evaluate industry and biosystems. They can be useful for research or commercial purpose, and can help make decisions in pre-commercial stage and optimization in on-going operation.

1.2 Life Cycle Assessment (LCA)

Environmental consideration becomes more important during industry and agriculture as the world population grows rapidly and pollutions spread worldwide. There

are various developed methods to evaluate environmental impacts during product manufacture and service process, such as Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA), Ecological Footprint, Environmental Risk Assessment (ERA), Strategic Environmental Assessment (SEA), Cost-Benefit Analysis (CBA), and Material Flow Analysis (MFA) (Finnveden et al., 2009). LCA is an approach to assess the environmental burden during a product manufacture or a service processing. Material and energy input will be analyzed, as well as the outputs, which may include products, byproducts, air emission, solid and fluid waste. Unit environmental impacts are the variables of concern. Since LCA can characterize and quantify material and energy flows during the cradle to grave life cycle, to calculate unit material and resource use, and to specify unit waste emission, it provides a system method to evaluate the processes and products (Du et al., 2010).

In general, a complete LCA contains four stages: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. The relationships of these four stages can be described as life cycle assessment framework, and is shown in Figure 1.1 (ISO, 2006). In the first stage, the reason and the purpose of a LCA study will be indicated, and the system boundaries and the functional unit will be defined (Finnveden et al., 2009). The functional unit is the unit that can be quantitatively calculated to represent the function provided by a product or a service (Finnveden et al., 2009). LCI is the stage to locate and quantify the inputs and outputs within the system boundaries. LCIA is the step to classify all the impacts, normalize impacts values, weigh those values according to various standards and concerns, so the significance and magnitude of the potential environmental impacts can be understood (ISO, 2006).

Interpretation helps understand LCA results in relation to the goal definition stage of the LCA study, so conclusions and recommendations for improvement can be achieved (ISO, 2006).

LCA is considered to be a comprehensive method to evaluate and compare the environmental impacts through a product's or service's life cycle; however, the accuracy of LCA is thought to be one of the faults (Reap et al., 2008). The system boundaries selection, functional unit definition, environmental impacts allocation, spatial variations, and data validations all bring uncertainty to LCA study (Reap et al., 2008). It is expected that LCA will be more elaborated in the next few years (Guinee et al,. 2011), because the development of impact assessment methods, regionalized databases, and methods for uncertainty analysis (Zamagni et al., 2010).

1.3 Techno-Economic Analysis (TEA)

To design a commercial-scale industry or biosystem, and to make a decision for investment, the facility and equipment information must be collected first, and investment and profits must be calculated. Techno-economic analysis (TEA) is a tool to evaluate the potential costs and profits based on assumed equipment and facility characters and costs (Petter and Tyner, 2014). TEA is a useful method for various industrial and biosystems evaluation, such as the evaluation of mobile broadband services (Frias and Pérez, 2012), biofuel production (Kazi et al., 2010; Vlysidis et al., 2011), and ammonia production from biomass gasification (Andersson and Lundgren, 2014). Since TEA can combine engineering design, technical information, and costs and profits together, it can provide

support not only for a long-term business strategic decision, but also for on-going operation and improvement (Knoll, 2012).

To conduct a TEA, system boundaries and flowchart are required, reasonable assumptions are necessary, and major technical and economic parameters must be identified. Then according to all the parameters, a mass and energy balance model is achieved. Based on the model, capital and operating costs are calculated, and profits are also calculated to evaluate the economic potential. According to Wallace (2011), from preliminary design to final commercial launch, for different stages, TEA can be conducted with different levels of rigor. Sensitivity analysis is a special step in TEA. It is the process to test various results when changing process and parameters in the flow diagram (Wallace, 2011), so it can help focusing elements to be optimized (Knoll, 2012).

1.4 DDGS Fractionation

With the continuously expanding consumption of fossil fuel, people not only have to face increasing fuel prices, but they also have to suffer under more severe air pollution. Many countries have already begun to explore a more environmentally friendly energy: biofuel. Bioethanol is mostly made from corn or sugarcane, and it is widely used in the U.S. and Brazil. In 2012, biofuels' consumption in the U.S. reached up to 13.8 billion gallons, which was about 7.1% of total transport fuel consumption (USDA, 2013).

Ethanol is the most important biofuel in the U.S. Ethanol can be either used as pure fuel for vehicles or as a gasoline additive. It will increase the octane rating, which is an indicator of the performance of a motor or aviation fuel; and it will also decrease vehicle emissions.

Distillers dried grains with solubles (DDGS) are co-products from corn ethanol fermentation. The main components of DDGS are protein, oil, fiber, and ash (Rosentrater and Muthukumarappan, 2006). One of the most important uses of DDGS is feed for animals, such as cattle, swine, fish and poultry. However, since some animals cannot digest fiber effectively, it is necessary either to add other ingredients, or to fractionate DDGS.

DDGS typically contains about 29% protein, 10% oil, 9% crude fiber and 5% ash (Lim and Yildirim-Aksoy, 2008).The average DDGS price was reported as $243.50 per US ton in April, 2014 (USDA, 2014). In order to improve its economic value, we could separate DDGS into a higher protein fraction, which can be used as animal feed; and a higher fiber fraction, which could be used as raw material for lignocellulosic ethanol production (Singh et al., 2002). According to Belyea et al., (2004), the price of DDGS with high oil (13%) and high protein (33%) contents could be $5–20 higher per US ton than regular DDGS. DDGS production increases rapidly as bioethanol production expands (Liu and Rosentrater, 2011). It was reported that about 35.84 million metric tons of DDGS were produced during the crop year 2012--2013 (AGMRC, 2014). The DDGS marketing potential is promising if we can achieve high protein from DDGS.

Research has found that chemical composition of DDGS can be related to particle size, shape and density (Bhadra et al., 2009). The smallest and densest DDGS particles have the potential of being rich in protein and low in fiber (Liu, 2008; Liu, 2009). Fractionation is a reasonable way to increase protein and decrease fiber from DDGS. Fractionation can be classified into wet fractionation and dry fractionation. Most studies have focused on dry fractionation because it requires less investment and simpler equipment.

Some research has been done on the fractionation of DDGS. However, all of them have their limits. Some studies do not get ideal protein percentage, while others have to use complicated equipment. Besides, no study has explored fractionation using gravity separator.

The combination of sieving and winnowing, known as the elusieve process, is the most promising of different dry fractionation processes (Srinivasan et al., 2009). In this process, DDGS was first sieved into several fractions and then blown by air. Because of the resulting elimination of small-sized non-fibers, it could be effective in separating fiber (Srinivasan et al., 2008). After elusieve processing, DDGS protein could increase by 2.3% (Srinivasan et al., 2013). However, it required three air classification unit operations, which made the process complex. In addition, the increase of protein, which varied according to different samples, was not ideal.

In Liu's study (2009), sieving winnowed DDGS fractions and winnowing sieved DDGS fractions were shown to have similar effectiveness in shifting component contents. The effectiveness of sieving, winnowing and their combinations was explored. Winnowing sieved DDGS fractions was recommended as the better choice because it required less time. However, this method still required an air fractionation process during the subfraction.

In the study conducted by Garcia and Rosentrater (2012), DDGS was first sieved using screening and the oversize fraction was milled into small particles. Then DDGS was processed using an aspirator into different fractions. This process was thought to be effective and less complex since only one air fractionation equipment was required during this process (Garcia and Rosentrater, 2012). However, in order to produce a single stream with a narrow particle size distribution, it still had to use a mill.

A study of fractionation by destoner was conducted, which was “a simple and efficient process to remove stones and soil from grains” (Zhang and Rosentrater, 2013). When it run with an 8 °angle and 27.5% air flow, the heavy fraction could achieve a 31.3% protein level. Destoner fractionation had higher efficiency and low cost compared with other methods and it was somewhat effective to separate oil fractions of DDGS. However, it was not as ideal to get high protein fraction. More studies need to be explored about how to adjust the operating parameters of the destoner.

1.5 Aquaponics

The term sustainable agriculture was explained as integrated systems of combing plant and animal production using ecologic applications. The long term goals of sustainable agriculture include:1) meeting human food needs; be environmentally friendly; 2) making full use of nonrenewable resources; 3) sustaining both economy and ecology; 4) improving life quality for not only farmers, but for the community and the society (NALC, 1990).

Aquaponics is the system combining hydroponic and aquaculture, in which aquatic animals and plants are raised together, and is considered as a mutually beneficial system (Love et al, 2014). Hydroponic crop production is a technology that plant roots grow in nutrient solution instead of soil, with or without other mechanical support (Jensen, 1997). Due to the non-soil culture of plants, aquaponics on some extent involves much less pathogens than traditional agriculture (Lacheta et al, 2010). The aquatic waste can be used as fertilizer for plants, and biofilters can remove other toxic components to maintain proper living environment for fish. When the system is maintained properly and in a balanced status, aquaponics will mimic the natural ecosystem, use much less water than traditional

aquaculture, and have minimal effluent, as a result, it is thought environmental friendly and as a sustainable agriculture (Blidariu and Grozea, 2011). For developing countries with limited fresh water, aquaponics has the potential to provide protein and vegetables in a sustainable way (Nichols and Savidov, 2012).

The operation of aquaponic systems provides the possibility and opportunity to produce fresh food in the backyard and building roof, which means urban people have more chance to consume local food. While some hobbyist operate small scale aquaponics outdoors, such as in the backyard or on the building roof, most commercial aquaponics operators, however, choose greenhouse or other indoor facility to control the environment (Licamele, 2009), in order to maintain food quality and safety, as well as to pursue maximum production yield, especially in areas with cold air temperatures. Greenhouse overcomes the short growing season in cold area; also it increases plant yield using supplementary light (Hamamoto and Yamazaki, 2011).

Although aquaponics is not a new technology, the popularity and development are still in their early age. According to a survey conducted by Love et al. in 2013, the median year for aquaponics operators began their practice is in 2010 and a large proportion of workers are volunteers and part-time workers (Love et al, 2015). The survey also reported that most operators design aquaponic systems by themselves rather than hiring specific engineer or consultant, which indicated there were large knowledge gaps for public and the increasing popularity of aquaponics may have large potential for creating job opportunities.

In terms of plant culture in aquaponics, there are various methods and media for plant support and production, and rafts are the most typical one (Love et al., 2015). Rafts are polystyrene or other synthetic aromatic polymer material which can float on the top of

water. When used in aquaponics, according to the type of the plant, holes with different diameters and spacing will be made in the raft. The plants will be placed in net pots and the net pots will be inserted into the holes in the raft. Other common methods include media beds, which use clay pebbles or expanded shale to support plants; wicking beds, which use natural absorptive media such as coconut coir instead of other typical materials in media beds; nutrient film technique (NFT) is a system that shallow water with all the nutrients required by plants go through plant roots in a channel; vertical towers are facilities where plants are set in a vertical system and water is pumped at intervals to go through the roots; dutch buckets are another type of plant container filled with soilless media, and water with nutrients floods the system periodically (Love et al., 2015). According to the survey conducted by Love et al. in 2013, almost 70% of aquaponics operators chose two or more methods during the plant production (Love et al., 2015).

Tilapia (*Oreochromis niloticus*) and basil (*Ocimum basilicum*) are the two species that most operators chose in their aquaponics (Love et al, 2015), which can be considered as model species for aquaponics. Originally coming from Africa, the hardy tilapia are fast growing tropical fish, and now are raised in the U.S. in both outdoor and indoor environments (AgMRC, 2014). Tilapia is thought to be the model species for aquaponics due to several reasons. The most important reason is the popularity and market potential. According to the national fishery institute, tilapia was reported to become the fourth popular sea food in the United States in 2012 (NFI, 2012). The other reason of widely raised by aquaponics operators is that they have the ability of surviving in poor water quality so they are easy to deal with in tanks or ponds; besides, they have the potential to grow to high density in confinement (Popma et al, 1996). Other commonly raised fish

include ornamental fish and catfish. Basil is a model aquaponics plants because it grows fast and it is resistant to insects, another more important reason is that it can be cultivated in a 28 days circle from transplanting to harvest (Rokacy, 2004), so it is convenient to do seeding, transplanting and harvesting. Besides, basil has the relatively higher retail prices than other crops, which makes it have the potential to make profit. Salad greens, other herbs except basil, tomato, and head lettuce are other popular plants (Love et al., 2015).

Originally arising from the mid of 1970s, aquaponics was first introduced to recirculating aquaculture systems using plants to help maintain water quality in fish culture (Lewis et al., 1978). How to maintain water quality is an inevitable problem when operating aquaponics and ammonia level is a major concern. Fish excrete ammonia, which is a metabolic product, through their gills and urine (Sace and Fitzsimmons, 2013). When Ammonia is accumulated to the level of above 0.05 mg/L, it is thought to be toxic for most fish (EDIS, 2012). During the aquaponics cycle, the process of nitrification is the conversion of ammonia to nitrite, and then to nitrate. The two groups of bacteria for fulfilling these two steps are *Nitrosomonas* and *Nitrobacter* (Rakocy 2006). While nitrite is toxic to fish, nitrate is considered non-toxic and can be utilized by plants as nutrient. pH is another daily monitoring indicator when operating aquaponics, and the suggested water pH to optimize nitrification is 7.5-8.0 (Tyson et al, 2011). Other concerned water quality items include alkalinity, chloride, hardness, CO_2, and temperature.

There were some studies on aquaponics operation and mechanism, but most of them focus on research scale (Rakocy et al., 2006; 2012). Some researches focused on the conversion from fish waste to nutrients and the utilization of nutrients. Villarroel et al. (2011) conducted a study of integrating fish feeding rates and ion waste production for

strawberry tilapia aquaponics. Blidariu and Grozea (2011) suggested that the selection of plant species should be adapted to the fish stocking density and subsequent nutrient concentration: Herbs, lettuce and other greens, which have relatively low nutrient requirement compared with other plants, are more suitable to grow in aquaponics. Graber and Junge proved that a special design of trickling filters, which was called light-expanded clay aggregate (LECA), was able to prompt nutrient recycling in aquaponics (Graber and Junge, 2009). It was reported that most of the nutrients would be sufficient in the aquaculture effluent when ratio of daily feed input and plant growing area is maintained well (Rakocy et al., 2003). In the commercial-scale tilapia and basil aquaponics operated by the University of Virgin Island (UVI), those nutrients that need to be supplemented to batch cultured basil are calcium, potassium, and iron, and no nutrient needs to be supplemented to staggered production (Rakocy et al., 2004). It was considered that the nutrient demands of different age plants could counterbalance for each other.

Recently, researches mainly focused on how to optimize aquaponics operation. The study conducted by Petrea et al. in 2013 concluded that the nitrite and nitrate content of spinach could be affected by plant density, and they also stated that spinach-trout aquaponics met food safety requirement (Petrea et al., 2013). Some studies focused on the hydraulic loading rate and plant ratio (Endut et al, 2010); while others focused on calcium and phosphorous dynamic (Petrea et al, 2014). A study conducted by Liang and Chien in 2013 suggested that increasing feeding frequency and extending photo period would increase fish and plant yield, and decrease water nitrogen and phosphorus accumulation (Liang and Chien, 2013). It was also reported that the introduction of freshwater prawn to

vegetable tilapia aquaponics increased system stability, diversity and yield (Sace and Fitzsimmons, 2013).

There were a handful studies related to the cost and profit for commercial scale aquaponics (Bailey et al., 1997; Tokunaga et al., 2013; Bunyaviroch et al., 2013), but these studies were conducted in tropical area and without the consideration of harsh winter weather like the mid-west U.S. The study conducted by Bailey et al. in 1997 was in the U.S. Virgin Islands, so neither greenhouse nor equipment designed to heat the greenhouse was considered in the analysis, and there were no supplemental lights, either. Besides, this study was not a complete TEA, and did not consider cost and profit on a base of a functional unit. The study conducted by Tokunaga et al. was in Hawaii and it concluded that the economic performance for commercial scale aquaponics had some potential, even though the potential might be not as promising as former studies suggested. The study conducted by Bunyaviroch et al. (2013) investigated a commercial case in Puerto Rico and indicated that aquaponics was viable there but the profitability was limited. Palm et al. conducted a study focusing on factors affecting economic sustainability of closed ebb flow aquaponics in Germany (Palm et al, 2014). Based on a techno-economic study of aquaponics in South Africa, Lapere concluded that high capital and operating cost made it difficult to make profit (Lapere, 2010); however, the natural and economic environments are quite different in South Africa and in the mainland of U.S.

In 2013, Love et al. conducted a relatively comprehensive international survey on aquaponics production and profitability (Love et al., 2015). It indicated that energy, water, and fish feed were the three major physical inputs in aquaponics. The sizes of aquaponics varied from tens to thousands of US gallon water volume according to different operating

purpose. Small scale aquaponics could be operated in the backyard as hobby while commercial scale aquaponics was considered as agriculture which could make profit. It was reported that the average size of commercial aquaponics was using 10,300 L water and was occupying 0.01 ha field. Less than half operators also reported that they used supplemental light to help plant production. The survey also stated that electricity was the primary energy source for aquaponics.

Aquaponics is supposed to have large potential in development and expansion, and as reported by Love et al. in 2013, even for commercial operators, 55% of them harvested less than 45 kg fish and 52% of them harvested less than 226 kg plants in the previous year. The survey also showed that more commercial aquaponics producers sold products through direct markets, such as at aquaponics facility, farm market, and restaurant, other than indirect markets, such as via grocery store and wholesale; which also indicated that aquaponics was still not a mature agriculture. The survey also showed that only 31% of operators made profits during the previous year, and many of them were not only selling fish and plants, but also selling aquaponics materials and services (Love et al., 2015).

1.6 Conclusions

Both DDGS fractionation and the operation of aquaponics aim to make full use of materials and resources. There have been some researches (Srinivasan et al., 2008; 2009; 2013; Liu, 2009; Garcia and Rosentrater, 2012; Zhang and Rosentrater, 2013) about DDGS fractionation, but the process is still needed to be optimized to achieve better nutrient component separation. No LCA or TEA has been conducted to DDGS fractionation. There are some researches (Bailey et al., 1997; Rokacy, 2004; 2006; Villarroel et al., 2011; Petrea

et al., 2013; Tokunaga et al., 2013; Bunyaviroch et al., 2013; Sace and Fitzsimmons, 2013; Love et al, 2014; 2015) on aquaponics, including nutrient cycle and economic cost and profit of various aquaponics systems, but no complete LCA and TEA has been conducted to aquaponics located on mainland of U.S., which indicates there are some data gaps to explore more in the future.

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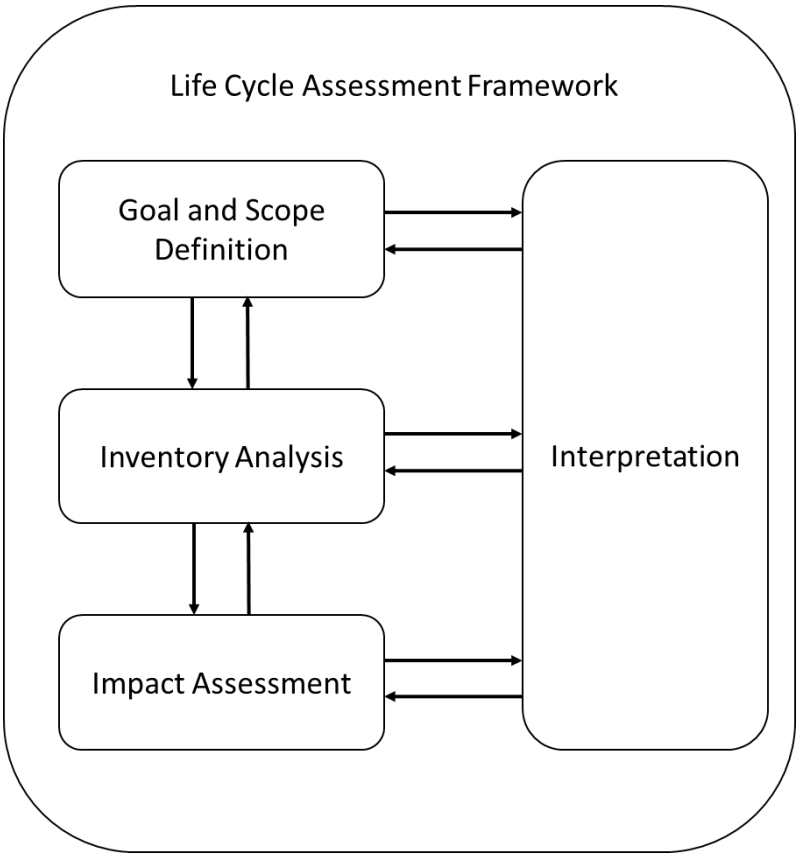

Figure 1.1. Life cycle assessment framework.

CHAPTER 2

OBJECTIVES AND HYPOTHESES

This study aimed to optimize the process of DDGS fractionation through a gravity separator, and conduct LCA and TEA for DDGS fractionation and aquaponics. The objectives and hypotheses were as following:

(1) DDGS was firstly sieved into five size categories, then three categories and raw DDGS were further separated into light, mid-light, mid-heavy and heavy fractions using the gravity separator. Three parameters of a gravity separator were adjusted during the fractionation, including side slope, eccentric shaft vibration, and the air flow rate. Nutrient analysis was measured to determine the most effective combination for DDGS fractionation.

(H_A: DDGS fractionation through a gravity separator was found to be effective in getting substantial fractions enriched in protein and oil.)

(2) LCA and TEA were conducted on DDGS fractionation through a gravity separator based on the optimized parameters decided in the previous study. Three scales, including lab scale, pilot scale, and commercial scale of DDGS fractionation, were considered and analyzed.

(H_A: Both the environmental impacts and the cost per unit of DDGS fractionation decreased as the fractionation scale expanded. DDGS fractionation was profitable.)

(3) LCA and TEA of tilapia and basil aquaponics were conducted. Three scales, including a truly running system on Iowa State University campus, pilot scale, and commercial scale of aquaponics were considered and analyzed.

(H_A: The environmental impacts and cost based on functional unit decreased as operation scales expanded. Operating commercial aquaponics in Midwest U.S. was profitable.)

CHAPTER 3

FRACTIONATION OF DISTILLERS DRIED GRAINS (DDGS) THROUGH A GRAVITY SEPARATOR: PROCESS OPTIMIZATION

This chapter is based on a manuscript to be submitted to *Cereal Chemistry*.

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Abstract

Distillers dried grains with solubles (DDGS) mainly contains protein, oil, fiber, and ash. DDGS could have more economic value and wider use if it could be separated into higher protein fraction and higher fiber fraction. Various ways have been explored in recent years, and two of the most effective processes are sieving and winnowing. In the present work, the optimization of three parameters of a gravity separator (side slope, eccentric shaft vibration, and the air flow rate), was conducted to separate DDGS. DDGS was firstly sieved into five size categories, then three categories and raw DDGS were further separated into light, mid-light, mid-heavy and heavy fractions using the gravity separator. By adjusting the three parameters, four combinations were tested. After Nutrient analysis, the best parameters were determined: the eccentric shaft vibration is 420 rpm, the side slope is 5^{o}, the airflow rate is 0.8890 m/s, and the DDGS category is 0.425-2.000 mm. This process was found to be effective in getting substantial fractions enriched in protein and oil.

Keywords

Distillers dried grains with solubles (DDGS), Fractionation, Gravity separator, Sifter, Fraction, Protein.

3.1 Introduction

Distillers dried grains with solubles (DDGS) are co-products of ethanol fermentation. DDGS typically contains around 29% protein, 10% oil, 9% crude fiber and 5% ash (Lim and Yildirim-Aksoy, 2008). The most typical use of DDGS is feed for animals, such as cattle, swine, fish, and poultry. However, since some animals cannot digest fiber effectively, it is necessary either to add other ingredients, or to fractionate DDGS. DDGS could have more economic value and wider use if it could be separated into higher protein fraction and higher fiber fraction. Various ways have been explored in recent years, and two of the most effective processes are sieving and winnowing. As reviewed in Chapter 1, the processes of different fractionations are either too complicated, or not efficient. Optimization of DDGS fractionation is still needed to be explored.

3.2 Materials and Methods

3.2.1 Materials

Our study aimed to use a gravity separator to fractionate DDGS. The gravity separator is designed to separate different particles according to their density and can be useable on any dry particle stream. In our study, we focused on how to better separate the high-protein particles through the gravity separator in a more simple and efficient way with reasonable cost. DDGS was sieved into five size categories, and then three categories and raw DDGS were further separated using a gravity separator. The side slope of the deck, the eccentric shaft vibration, and the air flow rate were adjusted. The combinations of two side slope and two eccentric shaft vibrations were operated. After that, nutrient analysis was

conducted to explore the most efficient parameters and the most proper particle size for DDGS fractionation.

DDGS used for the fractionation was collected from Lincolnway Energy, LLC in Nevada, Iowa (Figure 3.1). Samples were directly collected from the DDGS storage building. The DDGS were then stored in plastic tubs at room temperature ($23 \pm 1^{o}C$).

3.2.2 Methods

In this study, DDGS fractionation was conducted with a sifter and a gravity separator. A screw feeder was used to maintain a stable feeding rate. First, DDGS was sized using a round sifter (LS18_333, Sweco, Division No FM-I, L.L.C., Florence, KY, U.S., Figure 3.2). The screens were chosen according to standard procedure ANSI/ASAE S319.4 (ASABE 2008), using U.S. sieve nos. 10 (2.000 mm), 20 (0.850 mm), 40 (0.425 mm), and Pan (<0.425 mm). DDGS was first sized using 10-mesh and 40-mesh screens, and fractions of over 10 mesh (>2.000mm), 10--40 mesh (0.425--2.000mm) and through 40 mesh (<0.425 mm) were collected. Then fraction of 10--40 mesh was further sized using 20-mesh (0.850 mm) screen, and fractions of 10--20 mesh (0.850--2.000 mm) and 20--40 mesh (0.425--0.850 mm) were acquired. The process of sieving was shown in Figure 3.3. As shown in Figures 3.4 and 3.5, with a feeding rate of 29,260 g/h, during the first run of sizing, the mass percentage for 0.425--2.000 mm DDGS was 86.98% of the raw DDGS; and with a feeding rate of 32,793 g/h, during the second run of sizing, the mass percentage for 0.850--2.000 mm DDGS and 0.425--0.850 mm DDGS were 39.10% and 60.90% of the 0.425--2.000 mm DDGS, respectively.

Then, raw DDGS, and sized DDGS were further separated on a gravity separator (TKV25, Forsberg Incorporated, Thief River Falls, Minnesota, U.S.A., Figure 3.6). A steel

deck of 60-mesh (0.250 mm), with the size of 2’x 3’ (0.6096m * 0.9144m), was used on the gravity separator. The deck, which is fluidized by a pressurized air system, can blow the light materials to the top of the product bed and allow the heavy materials to contact the deck surface. The deck is powered by an eccentric drive, which moves the deck at low amplitude and high frequency up and down. This design makes the heavy materials contacting the deck surface move uphill, whereas the light materials fluidized by the air system move downhill due to gravitational pull. To attain a satisfied setup of the gravity separator, four combinations of two side slope and two deck frequency were explored and decided, using raw DDGS and the fraction of 0.425--2.000 mm DDGS. Two eccentric shaft vibrations, 420 rpm and 450 rpm, were selected, while the side slopes of 5 °and 6.5 °were selected. Then four categories, including raw DDGS, fraction of 0.425--2.000 mm, fraction of 0.850--2.000 mm, and fraction of 0.425--0.850 mm were run through the gravity separator under each of the four combinations, respectively. This resulted in 16 treatments in total, and the experimental design was shown in Table 3.1. To optimize the separation, airflow rates were adjusted according to different size fractions, ranging from 0.7620 to 1.5240 m/s. All the parameters were maintained stable during each collection of samples. Two replications were run for each fraction, and each run lasted for three minutes. Random order for treatments was selected to eliminate potential effects. Four fractions, which were named light, mid-light, mid-heavy, and heavy, were collected after each run (Figure 3.7). Totally, 128 samples were acquired after gravity separation. Then, the 128 samples, along with raw DDGS, fractions of > 2.000 mm, 0.425--2.000 mm, 0.850-2.000 mm, 0.425--0.850 mm, and < 0.425 mm were analyzed to explore the nutrient.

The nutrient analysis was conducted using a calibrated NIR Analyzer (DICKEY john INSTALAB 800, Instrumentvagen, Hagersten, Sweeden, Figure 3.8). Two replications were analyzed for each sample and 268 sets of data were collected. For each set of data, moisture (% w.b.), protein (% d.b.), oil (% d.b.), and fiber (% d.b.) were reported. Then a statistical data analysis was conducted using Microsoft Excel v. 2013 (Microsoft Corp, Redmond, WA), and JMP Pro.10 (SAS Institute, Cary, NC) software.

3.3 Results and Discussion

3.3.1 Results

Table 3.2 indicated nutrient composition for raw DDGS and five sized categories of DDGS prior to gravity separation. Figures 3.9-3.24 presented average nutrient composition for each fraction of DDGS treated by gravity separation under all experimental conditions. The moisture varied from 3.11% in the heavy fraction of 0.425-2.000 mm DDGS under the eccentric shaft vibration of 420 rpm, and the side slope of 6.5^{o}, to 8.93% in the light fraction of 0.850-2.000 mm DDGS under condition of under the eccentric shaft vibration of 450 rpm, and the side slope of 5^{o}, with an average of 5.45%. Compared to raw DDGS and unseparated categories of DDGS, the decrease of the average moisture might be due to the blow of the airflow. The protein varied from 22.95% in the light fraction of 0.850--2.000 mm DDGS under the eccentric shaft vibration of 450 rpm, and the side slope of 5^{o}, to 42.46% in the heavy fraction of 0.850--2.000 mm DDGS under the eccentric shaft vibration of 420 rpm, and the side slope of 5^{o}, with an average of 33.14%. Oil varied from 7.52% in the light fraction of 0.850--2.000 mm DDGS under the eccentric shaft vibration of 450 rpm, and the side slope of 5^{o}, to 23.20% in the mid-heavy

fraction of 0.850--2.000 mm DDGS under the eccentric shaft vibration of 420 rpm, and the side slope of 5°, with an average of 13.17%. Fiber varied from 6.02% in the light fraction of 0.850--2.000 mm DDGS under the eccentric shaft vibration of 450 rpm, and the side slope of 5°, to 6.53% in the heavy fraction of raw DDGS under the eccentric shaft vibration of 420 rpm or 450 rpm, and the side slope of 5°, with an average of 6.36%.

After gravity separation, fractions with various density also had influence on DDGS nutrient shift, so Table 3.3 showed main treatment effects on DDGS nutrient composition. The parameters contained particle size, side slope of the deck, eccentric shaft vibration, and fraction. Table 3.3 showed that particle size had effect on DDGS nutrient composition; side slope did not show effect on composition shift; eccentric shaft vibration had effect on other nutrient composition expect fiber; and fraction had effect on all nutrient composition. As shown in Table 3.4, statistical analysis across all treatment effect was conducted, at α=0.05. The result showed that interaction between independent variables, such as interaction between particle size and fraction, and particle size and eccentric shaft vibration, had significant effect on all four nutrient compositions. Tables 3.5-3.8 showed the 16 treatment combination effects on DDGS nutrient composition for light, mid-light, mid-heavy, and heavy fractions after gravity separation, respectively. All the data were given as mean ±SD. Levels not connected by same letters were significantly different.

3.3.2 Discussion

The protein percentage was the main indicator for DDGS price, however, the percentage of enriched DDGS to total DDGS should also be considered. The ultimate goal of gravity separation was to get enriched DDGS at reasonable cost. To explore the best parameters with high benefit, protein increase yield was considered as an indicator of

fractionation efficiency. Protein increase yield was the product of protein increase and total mass percentage. Protein increase was the difference of protein percentage of a certain fraction and the raw DDGS. Total mass percentage was the mass percentage of a certain fraction of the raw DDGS. The larger the protein increase yield, the higher efficient of DDGS fractionation. As shown in Table 3.9, there were two largest yields with 1.26% increase for protein. They were heavy fraction from 0.425--2.000 mm DDGS under the eccentric shaft vibration of 420 rpm, and the side slope of 5^{o}, and heavy fraction from 0.425--2.000 mm DDGS under the eccentric shaft vibration of 420 rpm, and the side slope of 6.5^{o}. Besides, mid-heavy fraction from 0.425--2.000 mm DDGS under the eccentric shaft vibration of 420 rpm, and the side slope of 5^{o}, also had relatively high protein increase yield of 0.65%. Based on all results, the best parameters were with the eccentric shaft vibration of 420 rpm, and the side slope of 5^{o}, with airflow rate of 0.8890 m/s, and the DDGS category should be 0.425-2.000 mm DDGS. The four fractions from 0.425--2.000 mm DDGS after gravity separation under optimized parameters were shown in Figure 3.25.

Although heavy fraction from raw DDGS under the eccentric shaft vibration of 450 rpm, and the side slope of 5^{o}, and heavy fraction from raw DDGS under the eccentric shaft vibration of 420 rpm, and the side slope of 6.5^{o}, also had relatively high protein increase yield, 1.17% and 1.07%, respectively, it was not recommended to do gravity separation without sizing. Due to the variance of particle size for raw DDGS, those particles with diameter less than 0.425 mm had the potential to block the deck.

Compared to previous DDGS fractionation in pilot scale (Srinivasan et al., 2009; Garcia and Rosentrater, 2012), the present study was simpler while the composition shift is obvious, especially for protein and oil. The well-known elusieve process sieved DDGS

to four size categories and aspirated three of them (Srinivasan et al., 2009), while the study conducted by Garcia and Rosentrater first screened DDGS, and milled the oversized DDGS to narrow the size distribution, and finally aspirated the milled DDGS(Garcia and Rosentrater, 2012). Both of the two processes were reported to be effective in shifting nutrient composition: the elusieve process shift protein up to 9.3 and fiber up to 14.3(Srinivasan et al., 2009), while the screening-milling-aspiration process shifted protein 8.34 and shifted fiber11.0. But the relatively complicated processes still prohibited the application in industry. The DDGS fractionation through a destoner was relatively easier to operate, however, the protein shift was not so ideal (Zhang and Rosentrater, 2013).

The present work used only two machines: sifter and gravity separator to fractionate DDGS. While the protein and oil shifts were competitive compared with other pilot studies, the fiber did not show obvious separation using different parameters of gravity separator. More work needs to be done to explore DDGS fractionation using various DDGS samples from different ethanol plants; and more gravity separator parameter combinations can be tested to improve the fractionation process.

3.4 Conclusions

The purpose of this study was to explore optimization of parameters for gravity separation of DDGS, and to find the most proper size category for economic benefit. Based on the nutrient component analysis and statistical analyses, the results showed that with the combination of an eccentric shaft vibration of 420 rpm, side slope 5^{o} of the gravity separator deck, and airflow rate of 0.8890 m/s, using size category of 0.425-2.000mm DDGS, the most economic benefit could be attained. In conclusion, DDGS fractionation

through a gravity separator was approved to be effective and economic to get high protein and high oil fractions.

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Table 3.1. DDGS fractionation experimental design.

Treatment	Eccentric shaft vibration (rpm)	Side slope (°)	Size category (mm)
1	420	5	Raw(0.725)
2	420	5	0.425-2.000
3	420	5	0.850-2.000
4	420	5	0.425-0.850
5	420	6.5	Raw(0.725)
6	420	6.5	0.425-2.000
7	420	6.5	0.850-2.000
8	420	6.5	0.425-0.850
9	450	5	Raw(0.725)
10	450	5	0.425-2.000
11	450	5	0.850-2.000
12	450	5	0.425-0.850
13	450	6.5	Raw(0.725)
14	450	6.5	0.425-2.000
15	450	6.5	0.850-2.000
16	450	6.5	0.425-0.850

Each treatment was replicated twice and all treatments were performed in a random order.

Table 3.2. DDGS nutrient composition prior to gravity separation.

Category	Particle size (mm)	Moisture* (% w.b.)	Protein* (% d.b.)	Oil* (% d.b.)	Fiber* (% d.b.)
Raw	0.725	7.59 ± 0.02^{a}	32.13 ± 0.16^{a}	10.57 ± 0.10^{a}	6.69 ± 0.01^{a}
Over 10	>2.000	$7.14 \pm 0.21^{a,b}$	37.05 ± 0.45^{b}	12.27 ± 0.31^{b}	6.59 ± 0.01^{b}
10-40	0.425-2.000	6.39 ± 0.01^{c}	31.43 ± 0.16^{a}	10.90 ± 0.02^{a}	6.40 ± 0.02^{c}
10-20	0.425-0.850	$8.17 \pm 0.25^{a,b}$	28.84 ± 1.06^{c}	11.84 ± 0.02^{b}	6.34 ± 0.01^{d}
20-40	0.850-2.000	7.13 ± 0.03^{d}	31.92 ± 0.21^{a}	10.99 ± 0.07^{a}	6.57 ± 0.01^{b}
Through 40	<0.425	$6.62 \pm 0.08^{b,c}$	34.42 ± 0.00^{d}	9.26 ± 0.06^{c}	6.66 ± 0.01^{a}

*All the data are given as mean ±SD. Levels not connected by same letters are significantly different.

Table 3.3. Main treatment effects on DDGS nutrient composition after gravity separation.

Parameter	Levels	Moisture* (% w.b.)	Protein* (% d.b.)	Oil* (% d.b.)	Fiber* (% d.b.)
Particle size (mm)	Raw (0.725)	5.25 ±1.34^{a,b}	34.25 ±4.81^{a}	14.05 ±5.29^{a,b}	6.41 ±0.11^{a}
	0.425-2.000	5.07 ±1.63^{a}	33.55 ±5.22^{a}	12.78 ±4.72^{a}	6.35 ±0.12^{b}
	0.850-2.000	5.57 ±1.85^{a,b}	33.90 ±6.60^{a}	15.89 ±5.85^{b}	6.34 ±0.16^{b}
	0.425-0.850	5.90 ±1.33^{b}	30.86 ±3.54^{b}	9.95 ±1.77^{c}	6.34 ±0.05^{b}
Side slope (º)	5	5.64 ±1.58^{a}	32.67 ±5.32^{a}	12.91 ±5.15^{a}	6.36 ±0.12^{a}
	6.5	5.26 ±1.56^{a}	33.61 ±5.27^{a}	13.43 ±5.12^{a}	6.36 ±0.11^{a}
Eccentric shaft vibration (rpm)	420	5.22 ±1.52^{a}	33.99 ±5.45^{a}	13.97 ±5.47^{a}	6.37 ±0.11^{a}
	450	5.67 ±1.60^{b}	32.29 ±5.04^{b}	12.37 ±4.66^{b}	6.35 ±0.13^{a}
Fraction	Light	7.37 ±0.62^{a}	27.19 ±1.56^{a}	8.53 ±0.57^{a}	6.27 ±0.11^{a}
	Mid-light	6.05 ±0.87^{b}	30.81 ±2.86^{b}	10.75 ±2.58^{b}	6.33 ±0.08^{b}
	Mid-heavy	4.57 ±0.93^{c}	35.48 ±3.66^{c}	15.01 ±4.80^{c}	6.39 ±0.10^{c}
	Heavy	3.80 ±0.64^{d}	39.09 ±2.66^{d}	18.38 ±4.22^{d}	6.45 ±0.08^{d}

*All the data are given as mean ±SD. Levels not connected by same letters are significantly different.

Table 3.4. Interaction results for particle size (PS), side slope (SS), eccentric shaft vibration (ESV), and fraction on DDGS nutrient compositions (p-values).

Interactions	Moisture (% w.b.)	Protein (% d.b.)	Oil (% d.b.)	Fiber (% d.b.)
PS	<0.0001	<0.0001	<0.0001	<0.0001
ESV	<0.0001	<0.0001	<0.0001	0.0275
SS	<0.0001	<0.0001	0.0209	0.7068
fraction	<0.0001	<0.0001	<0.0001	<0.0001
PS*ESV	<0.0001	<0.0001	<0.0001	0.0168
PS*SS	0.0068	0.0785	0.0387	0.5353
ESV*SS	0.0743	0.0162	0.0588	0.0910
PS*fraction	<0.0001	<0.0001	<0.0001	<0.0001
ESV*fraction	0.2244	0.0526	<0.0001	0.4057
SS*fraction	0.1027	0.0845	0.2024	0.7225
PS*ESV*SS	<0.0001	<0.0001	0.0002	0.2716
PS*ESV*fraction	0.1392	0.1014	0.0449	0.6526
PS*SS*fraction	0.6793	0.8337	0.6084	0.9926
ESV*SS*fraction	0.2873	0.3519	0.6584	0.7650
PS*SS*ESV*fraction	0.3935	0.6384	0.6348	0.9902

Table 3.5. Treatment combination effects on DDGS nutrient composition for light fraction after gravity separation.

TRT	ESV (rpm)	SS (º)	PS (mm)	Moisture* (% w.b.)	Protein* (% d.b.)	Oil* (% d.b.)	Fiber* (% d.b.)
1	420	5	Raw(0.725)	7.25 ±0.35^{c,d}	27.93 ±1.05^{a-d}	8.39 ±0.10^{c,d}	6.36 ±0.10^{a}
2	420	5	0.425-2.000	6.90 ±0.28^{c,d}	28.27 ±1.21^{a-c}	8.66 ±0.39^{c,d}	6.30 ±0.08^{a-c}
3	420	5	0.850-2.000	7.66 ±0.26^{b,c}	26.88 ±0.69^{c,d}	9.89 ±0.20^{a}	6.17 ±0.03^{b-d}
4	420	5	0.425-0.850	7.18 ±0.19^{c,d}	27.66 ±0.21^{b-d}	8.57 ±0.03^{c,d}	6.33 ±0.03^{a}
5	420	6.5	Raw(0.725)	6.67 ±0.14^{d}	29.22 ±0.19^{a}	8.60 ±0.42^{c,d}	6.35 ±0.02^{a}
6	420	6.5	0.425-2.000	6.91 ±0.31^{c,d}	28.46 ±0.41^{a,b}	8.87 ±0.23^{b,c}	6.32 ±0.10^{a,b}
7	420	6.5	0.850-2.000	7.69 ±0.30^{b,c}	26.44 ±0.82^{d}	9.45 ±0.41^{a,b}	6.15 ±0.02^{c,d}
8	420	6.5	0.425-0.850	7.12 ±0.07^{c,d}	27.38 ±0.40^{b-d}	8.34 ±0.10^{c,d}	6.28 ±0.04^{a-c}
9	450	5	Raw(0.725)	7.07 ±0.36^{c,d}	28.32 ±0.34^{a-c}	8.13 ±0.07^{d,e}	6.36 ±0.04^{a}
10	450	5	0.425-2.000	7.25 ±0.87^{c,d}	27.21 ±0.68^{b-d}	8.31 ±0.21^{c,d}	6.27 ±0.11^{a-c}
11	450	5	0.850-2.000	8.93 ±0.03^{a}	22.95 ±0.21^{f}	7.52 ±0.22^{e}	6.02 ±0.02^{d}
12	450	5	0.425-0.850	7.25 ±0.14^{c,d}	27.43 ±0.39^{b-d}	8.42 ±0.22^{c,d}	6.32 ±0.01^{a,b}
13	450	6.5	Raw(0.725)	7.24 ±0.63^{c,d}	27.74 ±0.42^{a-d}	8.09 ±0.16^{d,e}	6.34 ±0.10^{a}
14	450	6.5	0.425-2.000	7.24 ±0.22^{c,d}	27.33 ±0.48^{b-d}	8.31 ±0.15^{c,d}	6.30 ±0.07^{a-c}
15	450	6.5	0.850-2.000	8.26 ±0.34^{a,b}	24.80 ±0.67^{e}	8.55 ±0.45^{c,d}	6.11 ±0.03^{d}
16	450	6.5	0.425-0.850	7.40 ±0.10^{b-d}	27.10 ±0.35^{b-d}	8.48 ±0.08^{c,d}	6.30 ±0.04^{a-c}

*All the data are given as mean ±SD. Levels not connected by same letters are significantly different. TRT is treatment, ESV is eccentric shaft vibration, SS is side slope, and PS is particle size.

Table 3.6. Treatment combination effects on DDGS nutrient composition for mid-light fraction after gravity separation.

TRT	ESV (rpm)	SS (º)	PS (mm)	Moisture* (% w.b.)	Protein* (% d.b.)	Oil* (% d.b.)	Fiber* (% d.b.)
1	420	5	Raw(0.725)	5.72 ±0.67^{c-e}	31.97 ±0.67^{a-d}	10.46 ±0.07^{c-e}	6.37 ±0.07^{a}
2	420	5	0.425-2.000	5.73 ±1.28^{c-e}	31.54 ±4.77^{a-d}	10.85 ±3.04^{c-e}	6.34 ±0.14^{a}
3	420	5	0.850-2.000	4.81 ±0.55^{e}	35.82 ±1.39^{a}	16.94 ±1.60^{a}	6.42 ±0.02^{a}
4	420	5	0.425-0.850	7.05 ±0.28^{a-c}	27.93 ±0.86^{d}	8.62 ±0.12^{e}	6.31 ±0.03^{a}
5	420	6.5	Raw(0.725)	5.24 ±0.48^{d,e}	33.33 ±1.83^{a-c}	11.97 ±1.57^{c,d}	6.36 ±0.03^{a}
6	420	6.5	0.425-2.000	5.75 ±1.04^{c-e}	31.45 ±3.89^{a-d}	10.35 ±1.94^{c-e}	6.32 ±0.12^{a}
7	420	6.5	0.850-2.000	5.14 ±0.16^{e}	34.32 ±0.41^{a,b}	15.43 ±0.82^{a,b}	6.37 ±0.02^{a}
8	420	6.5	0.425-0.850	6.64 ±0.39^{a-d}	28.16 ±0.46^{d}	8.84 ±0.18^{e}	6.27 ±0.03^{a}
9	450	5	Raw(0.725)	6.07 ±0.16^{a-e}	30.70 ±1.06^{b-d}	9.57 ±0.60^{d,e}	6.36 ±0.07^{a}
10	450	5	0.425-2.000	6.01 ±0.16^{a-e}	30.10 ±1.42^{b-d}	9.39 ±0.51^{d,e}	6.29 ±0.14^{a}
11	450	5	0.850-2.000	7.37 ±0.23^{a}	27.33 ±0.46^{d}	9.65 ±0.55^{c-e}	6.22 ±0.01^{a}
12	450	5	0.425-0.850	7.19 ±0.29^{a,b}	27.90 ±0.84^{d}	8.66 ±0.32^{e}	6.33 ±0.02^{a}
13	450	6.5	Raw(0.725)	5.82 ±0.50^{b-e}	31.10 ±0.83^{a-d}	9.72 ±0.52^{c-e}	6.35 ±0.14^{a}
14	450	6.5	0.425-2.000	5.78 ±0.60^{b-e}	30.71 ±2.61^{b-d}	9.59 ±1.11^{c-e}	6.31 ±0.11^{a}
15	450	6.5	0.850-2.000	5.90 ±0.40^{b-e}	31.32 ±1.06^{a-d}	12.66 ±1.41^{b,c}	6.32 ±0.03^{a}
16	450	6.5	0.425-0.850	6.56 ±0.21^{a-d}	29.31 ±0.74^{c,d}	9.34 ±0.29^{d,e}	6.34 ±0.03^{a}

*All the data are given as mean ±SD. Levels not connected by same letters are significantly different. TRT is treatment, ESV is eccentric shaft vibration, SS is side slope, and PS is particle size.

Table 3.7. Treatment combination effects on DDGS nutrient composition for mid-heavy fraction after gravity separation.

TRT	ESV (rpm)	SS (º)	PS (mm)	Moisture* (% w.b.)	Protein* (% d.b.)	Oil* (% d.b.)	Fiber* (% d.b.)
1	420	5	Raw(0.725)	4.19 ±0.28^{b,c}	37.44 ±1.56^{a-d}	18.09 ±1.17^{a-d}	6.46 ±0.07^{a}
2	420	5	0.425-2.000	4.48 ±1.17^{b,c}	35.52 ±5.68^{a-f}	14.77 ±6.06^{c-e}	6.36 ±0.15^{a}
3	420	5	0.850-2.000	3.65 ±0.21^{c}	40.86 ±0.55^{a}	23.20 ±0.93^{a}	6.49 ±0.03^{a}
4	420	5	0.425-0.850	5.54 ±0.25^{a,b}	31.52 ±0.52^{e-g}	9.65 ±0.13^{e}	6.34 ±0.02^{a}
5	420	6.5	Raw(0.725)	3.78 ±0.36^{c}	39.31 ±1.60^{a-c}	19.77 ±0.92^{a-c}	6.45 ±0.03^{a}
6	420	6.5	0.425-2.000	4.09 ±0.49^{c}	36.77 ±4.42^{a-e}	15.66 ±6.15^{b-e}	6.39 ±0.18^{a}
7	420	6.5	0.850-2.000	3.66 ±0.53^{c}	40.06 ±0.89^{a,b}	21.87 ±0.88^{a,b}	6.48 ±0.05^{a}
8	420	6.5	0.425-0.850	4.98 ±0.37^{a-c}	32.38 ±0.53^{d-g}	10.34 ±0.25^{e}	6.33 ±0.06^{a}
9	450	5	Raw(0.725)	4.69 ±0.17^{b,c}	34.55 ±1.60^{c-g}	13.59 ±1.63^{c-e}	6.39 ±0.11^{a}
10	450	5	0.425-2.000	3.76 ±1.13^{c}	36.01 ±0.88^{a-f}	13.67 ±0.35^{c-e}	6.36 ±0.11^{a}
11	450	5	0.850-2.000	6.18 ±0.18^{a}	31.01 ±0.58^{f,g}	12.52 ±1.66^{d,e}	6.34 ±0.09^{a}
12	450	5	0.425-0.850	6.23 ±0.07^{a}	29.89 ±0.19^{g}	9.29 ±0.32^{e}	6.33 ±0.01^{a}
13	450	6.5	Raw(0.725)	4.33 ±0.84^{b,c}	36.42 ±1.45^{a-f}	15.24 ±2.47^{b-e}	6.41 ±0.19^{a}
14	450	6.5	0.425-2.000	4.36 ±0.19^{b,c}	34.97 ±2.05^{b-g}	13.06 ±3.22^{c-e}	6.36 ±0.13^{a}
15	450	6.5	0.850-2.000	4.33 ±0.56^{b,c}	37.29 ±2.09^{a-d}	18.89 ±3.31^{a-d}	6.45 ±0.02^{a}
16	450	6.5	0.425-0.850	4.88 ±0.22^{a-c}	33.62 ±0.49^{d-g}	10.50 ±0.65^{e}	6.38 ±0.03^{a}

*All the data are given as mean ±SD. Levels not connected by same letters are significantly different. TRT is treatment, ESV is eccentric shaft vibration, SS is side slope, and PS is particle size.

Table 3.8. Treatment combination effects on DDGS nutrient composition for heavy fraction after gravity separation.

TRT	ESV (rpm)	SS (º)	PS (mm)	Moisture* (% w.b.)	Protein* (% d.b.)	Oil* (% d.b.)	Fiber* (% d.b.)
1	420	5	Raw(0.725)	4.07 ±0.36^{a-d}	40.42 ±1.15^{a-d}	21.47 ±0.90^{a,b}	6.53 ±0.09^{a}
2	420	5	0.425-2.000	3.39 ±0.26^{b-d}	39.27 ±3.82^{a-d}	18.14 ±4.97^{a-c}	6.42 ±0.11^{a}
3	420	5	0.850-2.000	3.69 ±0.40^{a-d}	42.46 ±0.37^{a}	22.87 ±1.21^{a}	6.47 ±0.04^{a}
4	420	5	0.425-0.850	4.44 ±0.27^{a,b}	34.97 ±0.69^{e,f}	12.17 ±1.18^{d,e}	6.40 ±0.02^{a}
5	420	6.5	Raw(0.725)	3.63 ±0.29^{a-d}	40.80 ±0.79^{a-c}	20.86 ±1.29^{a,b}	6.47 ±0.05^{a}
6	420	6.5	0.425-2.000	3.11 ±0.21^{d}	39.85 ±1.36^{a-d}	17.28 ±2.29^{b-d}	6.45 ±0.10^{a}
7	420	6.5	0.850-2.000	3.53 ±0.16^{a-d}	41.87 ±0.62^{a,b}	23.01 ±0.51^{a}	6.46 ±0.02^{a}
8	420	6.5	0.425-0.850	3.58 ±0.74^{a-d}	37.52 ±1.01^{c-f}	13.62 ±1.54^{c-e}	6.40 ±0.05^{a}
9	450	5	Raw(0.725)	4.38 ±0.23^{a-c}	39.03 ±1.71^{a-e}	20.59 ±1.27^{a,b}	6.53 ±0.07^{a}
10	450	5	0.425-2.000	3.16 ±1.17^{c,d}	40.24 ±0.81^{a-d}	20.25 ±0.80^{a,b}	6.46 ±0.13^{a}
11	450	5	0.850-2.000	4.66 ±0.51^{a}	37.76 ±2.18^{b-f}	19.04 ±2.26^{a,b}	6.47 ±0.04^{a}
12	450	5	0.425-0.850	4.45 ±0.34^{a,b}	34.65 ±1.10^{f}	11.77 ±1.17^{e}	6.38 ±0.02^{a}
13	450	6.5	Raw(0.725)	3.89 ±0.82^{a-d}	39.72 ±1.90^{a-d}	20.38 ±2.00^{a,b}	6.51 ±0.15^{a}
14	450	6.5	0.425-2.000	3.24 ±0.20^{b-d}	39.15 ±2.76^{a-e}	17.26 ±3.88^{b-d}	6.41 ±0.12^{a}
15	450	6.5	0.850-2.000	3.74 ±0.32^{a-d}	41.30 ±1.15^{a-c}	22.77 ±0.62^{a}	6.48 ±0.05^{a}
16	450	6.5	0.425-0.850	3.93 ±0.26^{a-d}	36.37 ±0.82^{d-f}	12.64 ±1.06^{d,e}	6.41 ±0.03^{a}

*All the data are given as mean ±SD. Levels not connected by same letters are significantly different. TRT is treatment, ESV is eccentric shaft vibration, SS is side slope, and PS is particle size.

Table 3.9a. Protein increase yield.

Particle size (mm)	Eccentric shaft vibration (rpm)	Side slope (°)	Fraction	Protein (% d.b.)	Protein increase (% d.b.)	Total mass percentage (%)	Protein increase yield* (%)
0.425-2.000	420	5	Heavy	39.27	7.14	17.68	1.26
0.425-2.000	450	6.5	Heavy	39.15	7.02	17.90	1.26
Raw (0.725)	450	5	Heavy	39.03	6.90	16.93	1.17
Raw (0.725)	450	6.5	Heavy	39.72	7.59	14.12	1.07
0.425-2.000	450	5	Mid-heavy	36.01	3.88	25.33	0.98
0.425-2.000	420	6.5	Mid-heavy	36.77	4.64	19.97	0.93
0.425-2.000	450	5	Heavy	40.24	8.11	10.90	0.88
0.425-0.850	420	6.5	Heavy	37.52	5.39	16.17	0.87
Raw (0.725)	420	5	Heavy	40.42	8.29	10.41	0.86
Raw (0.725)	450	6.5	Mid-heavy	36.42	4.29	19.66	0.84
0.425-2.000	420	6.5	Heavy	39.85	7.72	10.70	0.83
0.850-2.000	450	5	Heavy	37.76	5.63	13.84	0.78
0.425-0.850	450	5	Heavy	34.65	2.51	29.50	0.74
Raw (0.725)	420	6.5	Mid-light	33.33	1.20	60.40	0.72
0.425-0.850	450	6.5	Heavy	36.37	4.24	16.51	0.70
Raw (0.725)	450	5	Mid-heavy	34.55	2.42	28.33	0.69
0.850-2.000	450	6.5	Heavy	41.30	9.17	7.10	0.65
0.425-2.000	420	5	Mid-heavy	35.52	3.39	19.14	0.65
Raw (0.725)	420	6.5	Heavy	40.80	8.67	7.02	0.61
0.425-2.000	450	6.5	Mid-heavy	34.97	2.84	20.49	0.58
Raw (0.725)	420	5	Mid-heavy	37.44	5.31	10.64	0.56
Raw (0.725)	420	6.5	Mid-heavy	39.31	7.18	6.90	0.50
0.425-0.850	420	5	Heavy	34.97	2.84	17.37	0.49
0.850-2.000	420	5	Heavy	42.46	10.33	3.71	0.38
0.850-2.000	420	6.5	Heavy	41.87	9.74	3.36	0.33
0.850-2.000	420	5	Mid-light	35.82	3.69	8.75	0.32
0.850-2.000	420	6.5	Mid-heavy	40.06	7.93	3.34	0.26
0.850-2.000	450	6.5	Mid-heavy	37.29	5.15	4.88	0.25
0.850-2.000	420	6.5	Mid-light	34.32	2.19	9.72	0.21
0.850-2.000	420	5	Mid-heavy	40.86	8.73	2.16	0.19
0.425-0.850	450	6.5	Mid-heavy	33.62	1.49	11.80	0.18
0.425-0.850	420	6.5	Mid-heavy	32.38	0.25	13.88	0.03
0.425-0.850	420	5	Light	27.66	- 4.47	1.02	- 0.05
0.850-2.000	450	6.5	Mid-light	31.32	- 0.82	10.92	- 0.09
0.425-0.850	420	5	Mid-heavy	31.52	- 0.62	14.74	- 0.09
0.850-2.000	450	5	Mid-heavy	31.01	- 1.12	8.40	- 0.09
Raw (0.725)	420	5	Mid-light	31.97	- 0.16	64.26	- 0.10
0.425-0.850	450	5	Light	27.43	- 4.70	2.67	- 0.13
0.425-0.850	420	6.5	Light	27.38	- 4.76	3.26	- 0.16
0.425-2.000	420	5	Mid-light	31.54	- 0.59	26.71	- 0.16
0.425-0.850	450	5	Mid-heavy	29.89	- 2.24	10.66	- 0.24
0.425-2.000	420	6.5	Mid-light	31.45	- 0.68	36.64	- 0.25
0.850-2.000	450	5	Mid-light	27.33	- 4.80	6.30	- 0.30
0.425-2.000	450	5	Light	27.21	- 4.92	6.86	- 0.34
0.425-0.850	450	6.5	Light	27.10	- 5.03	6.91	- 0.35
0.425-0.850	450	5	Mid-light	27.90	- 4.23	10.15	- 0.43

*Protein increase yield is the product of protein increase and total mass percentage, which is an indicator of fractionation efficiency. Protein increase is the difference of protein percentage of a certain fraction and the raw DDGS. Total mass percentage is the mass percentage of a certain fraction of the raw DDGS.

Table 3.9b. Protein increase yield (continued).

Particle size (mm)	Eccentric shaft vibration (rpm)	Side slope (º)	Fraction	Protein (% d.b.)	Protein increase (% d.b.)	Total mass percentage (%)	Protein increase yield* (%)
0.725	450	5	Light	28.32	- 3.81	11.42	- 0.43
0.425-2.000	450	6.5	Mid-light	30.71	- 1.42	34.56	- 0.49
0.425-0.850	450	6.5	Mid-light	29.31	- 2.82	17.76	- 0.50
0.850-2.000	450	5	Light	22.95	- 9.18	5.48	- 0.50
0.725	450	6.5	Mid-light	31.10	- 1.04	50.13	- 0.52
0.725	420	5	Light	27.93	- 4.21	14.69	- 0.62
0.725	450	5	Mid-light	30.70	- 1.43	43.32	- 0.62
0.425-2.000	450	6.5	Light	27.33	- 4.80	14.03	- 0.67
0.725	450	6.5	Light	27.74	- 4.39	16.09	- 0.71
0.425-2.000	420	6.5	Light	28.46	- 3.67	19.66	- 0.72
0.725	420	6.5	Light	29.22	- 2.91	25.68	- 0.75
0.425-0.850	420	6.5	Mid-light	28.16	- 3.97	19.65	- 0.78
0.850-2.000	450	6.5	Light	24.80	- 7.33	11.11	- 0.81
0.425-0.850	420	5	Mid-light	27.93	- 4.21	19.84	- 0.83
0.425-2.000	450	5	Mid-light	30.10	- 2.04	43.89	- 0.89
0.425-2.000	420	5	Light	28.27	- 3.87	23.45	- 0.91
0.850-2.000	420	6.5	Light	26.44	- 5.69	17.59	- 1.00
0.850-2.000	420	5	Light	26.88	- 5.26	19.40	- 1.02

*Protein increase yield is the product of protein increase and total mass percentage, which is an indicator of fractionation efficiency. Protein increase is the difference of protein percentage of a certain fraction and the raw DDGS. Total mass percentage is the mass percentage of a certain fraction of the raw DDGS.

Figure 3.1. Raw DDGS collected from the Lincolnway Energy.

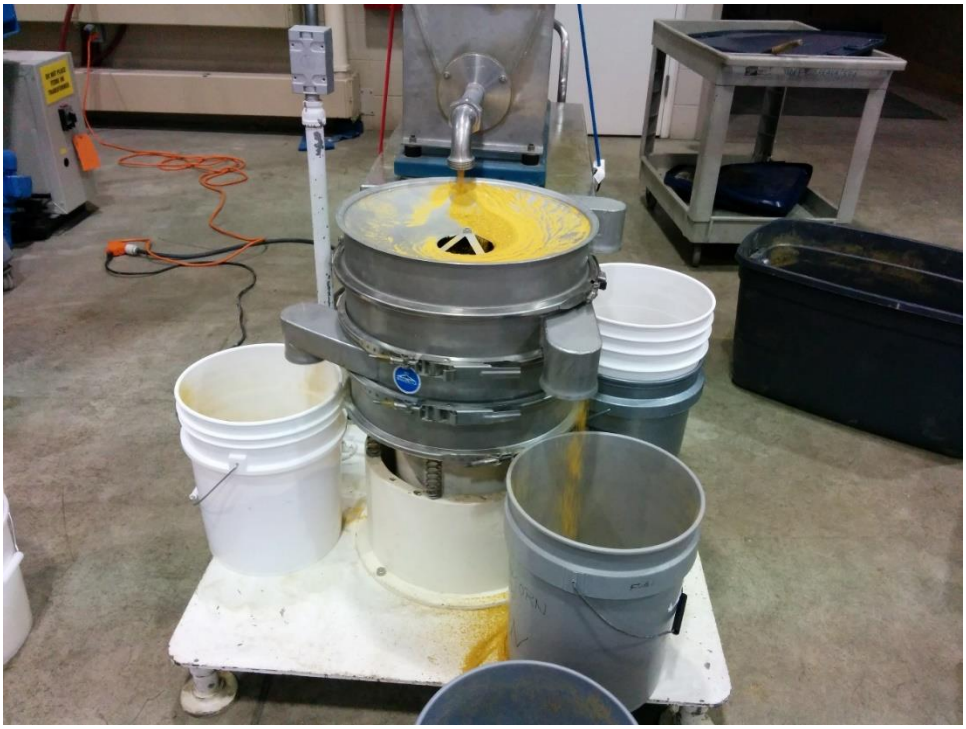

Figure 3.2. DDGS sieving using a round sifter Sweco LS18_333.

Figure 3.3. The process of DDGS sieving.

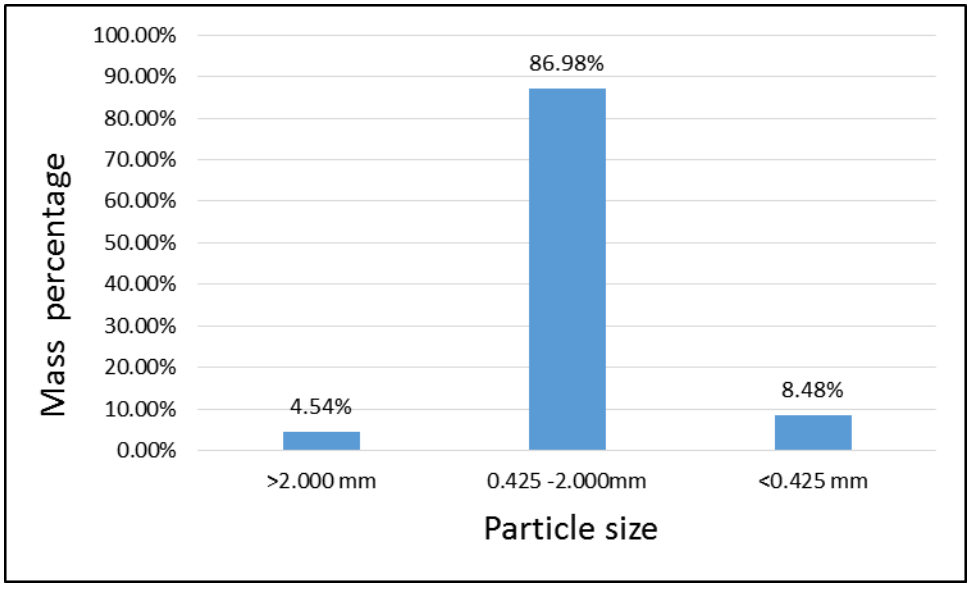

Figure 3.4. Weight distribution of three size categories after first run using sifter with a feeding rate of 29,260 g/h.

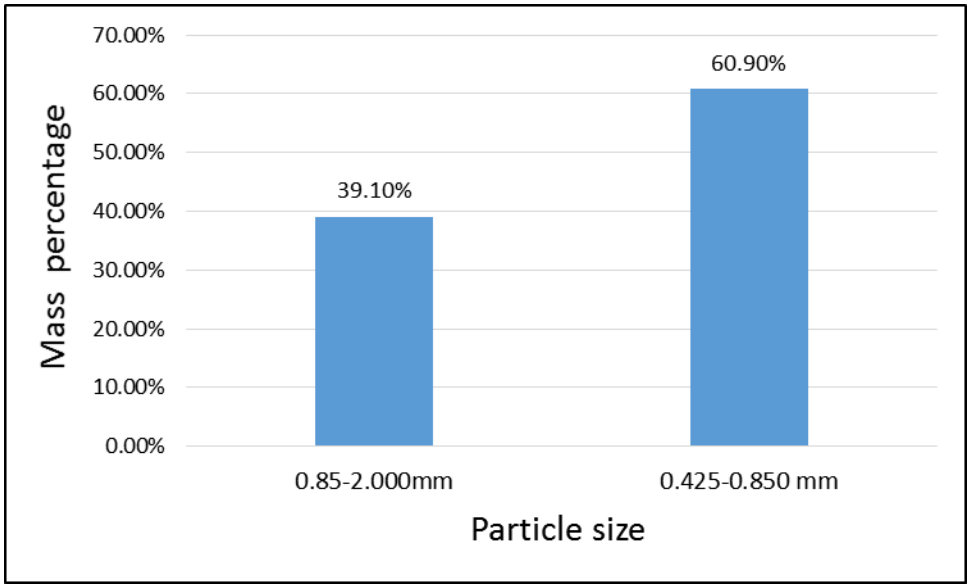

Figure 3.5. Weight distribution of two size categories after second run using sifter with a feeding rate of 32,793 g/h.

Figure 3.6. Forsberg TKV 25.

Figure 3.7. The collection of four fractions from gravity separation.

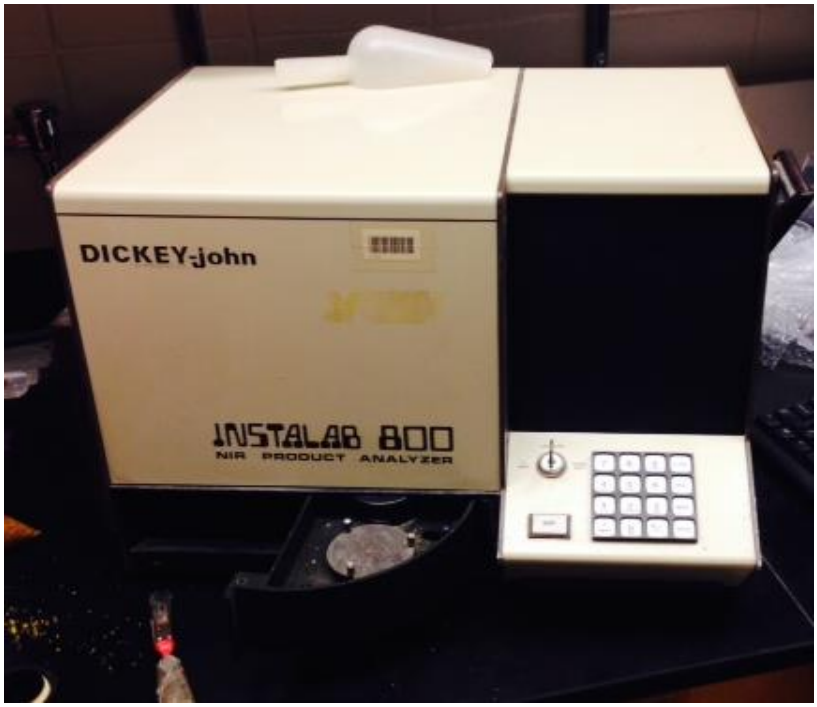

Figure 3.8. DDGS nutrient testing using DICKEY john INSTALAB 800.

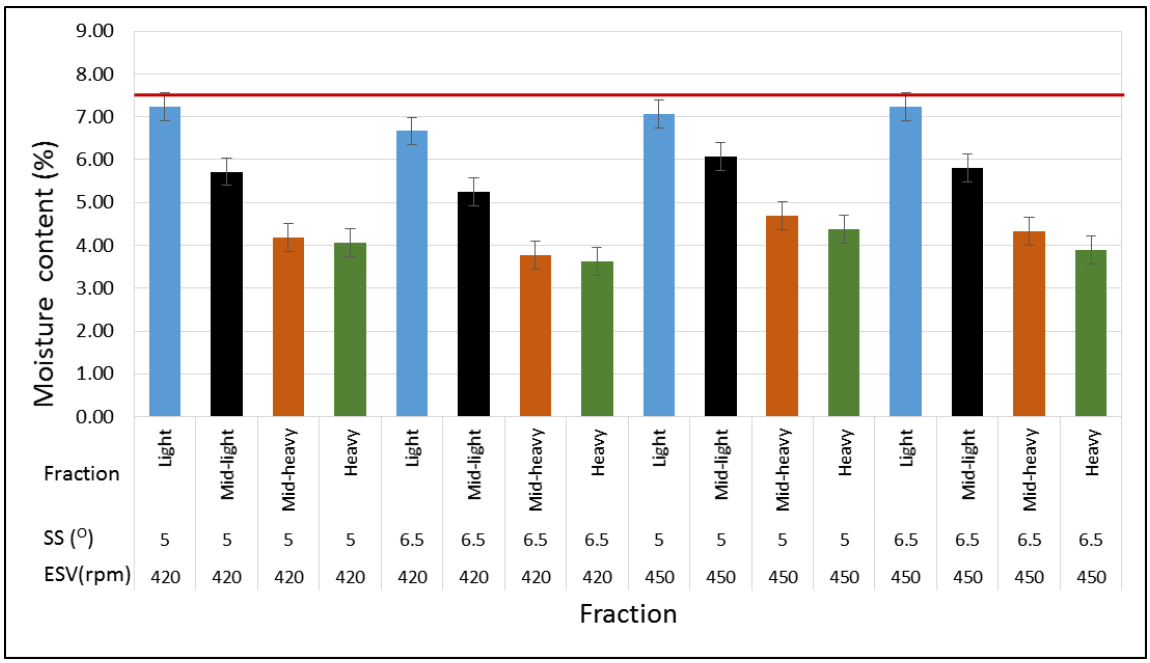

Figure 3.9. Moisture content for raw DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

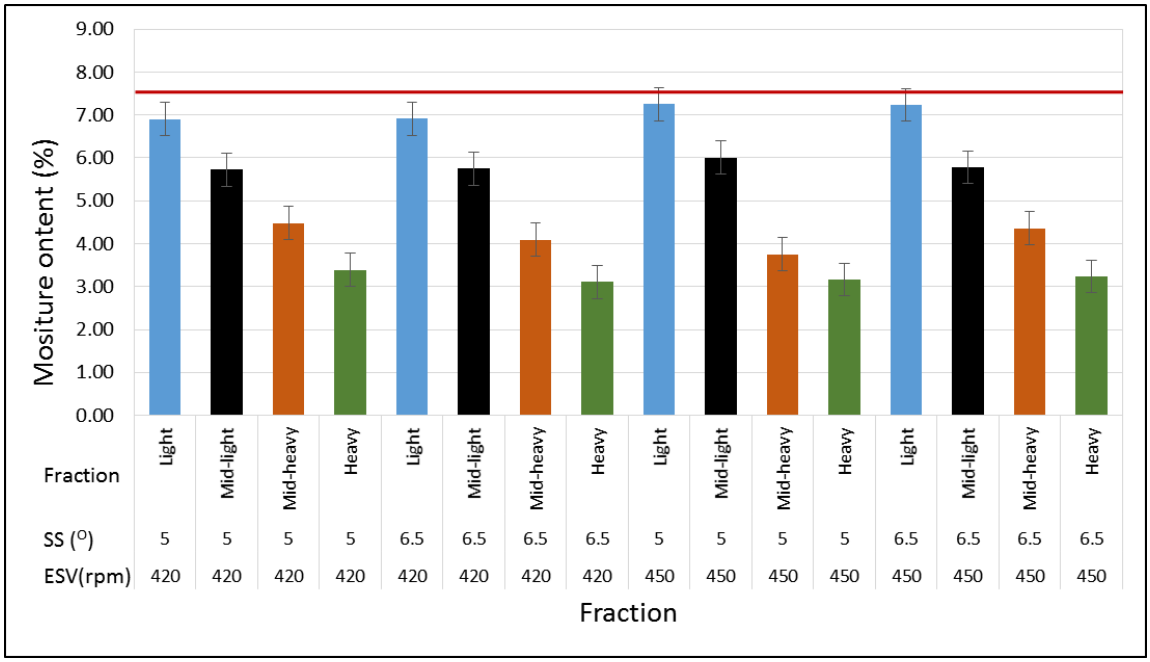

Figure 3.10. Moisture content for 0.425-2.000 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

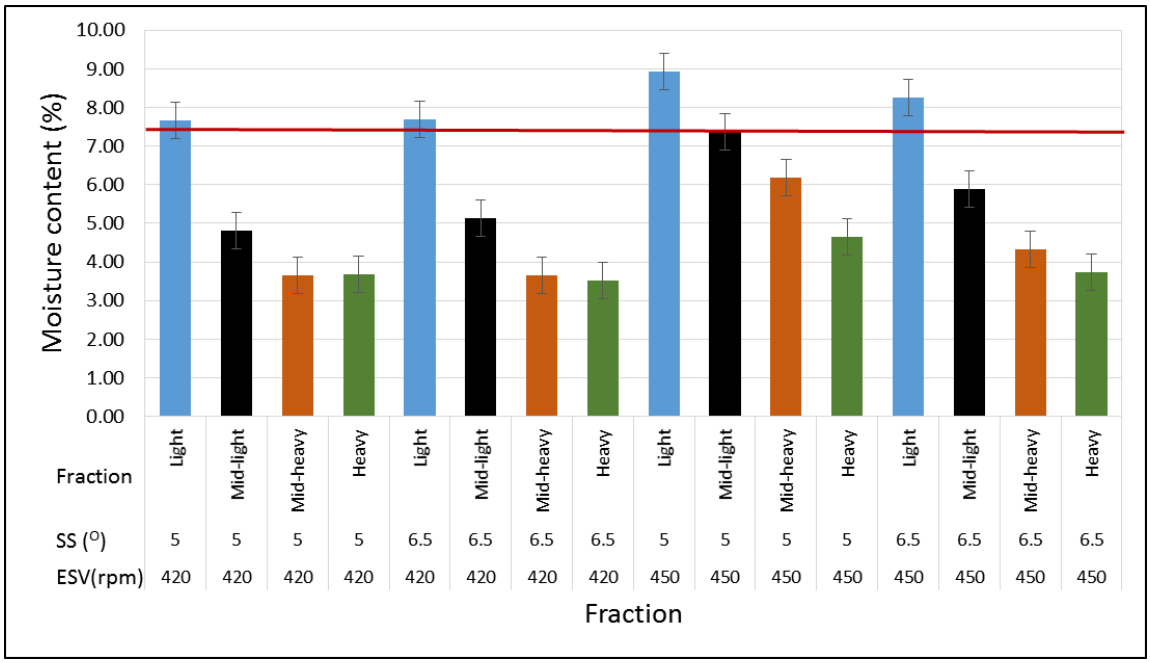

Figure 3.11. Moisture content for 0.850-2.000 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

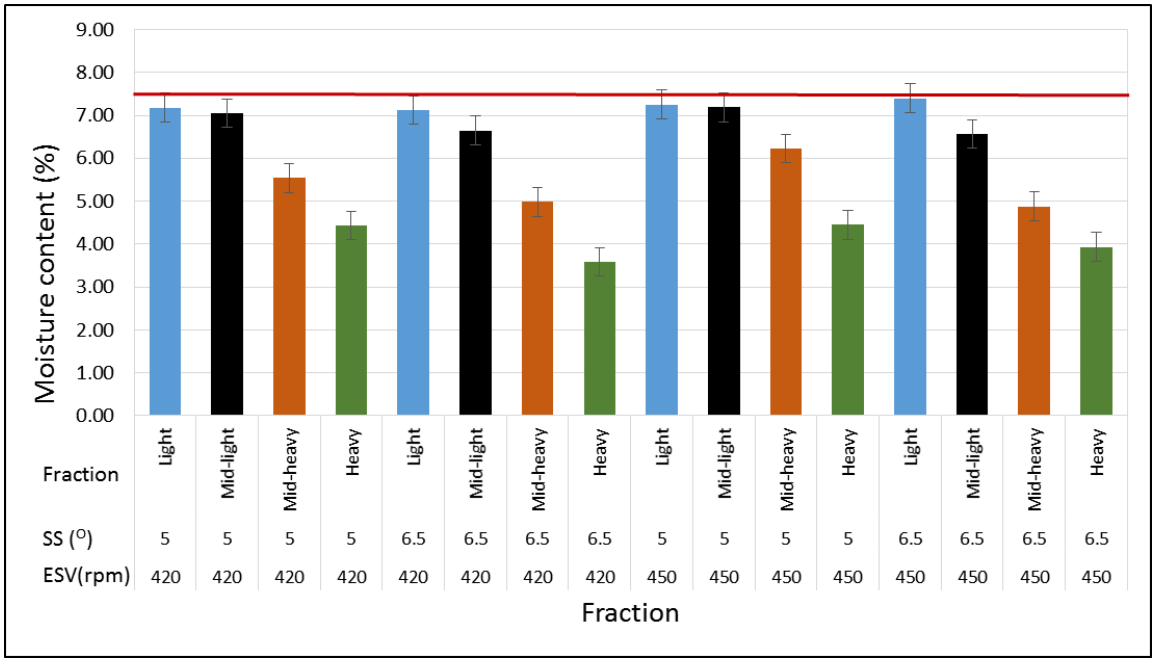

Figure 3.12. Moisture content for 0.425-0.850 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

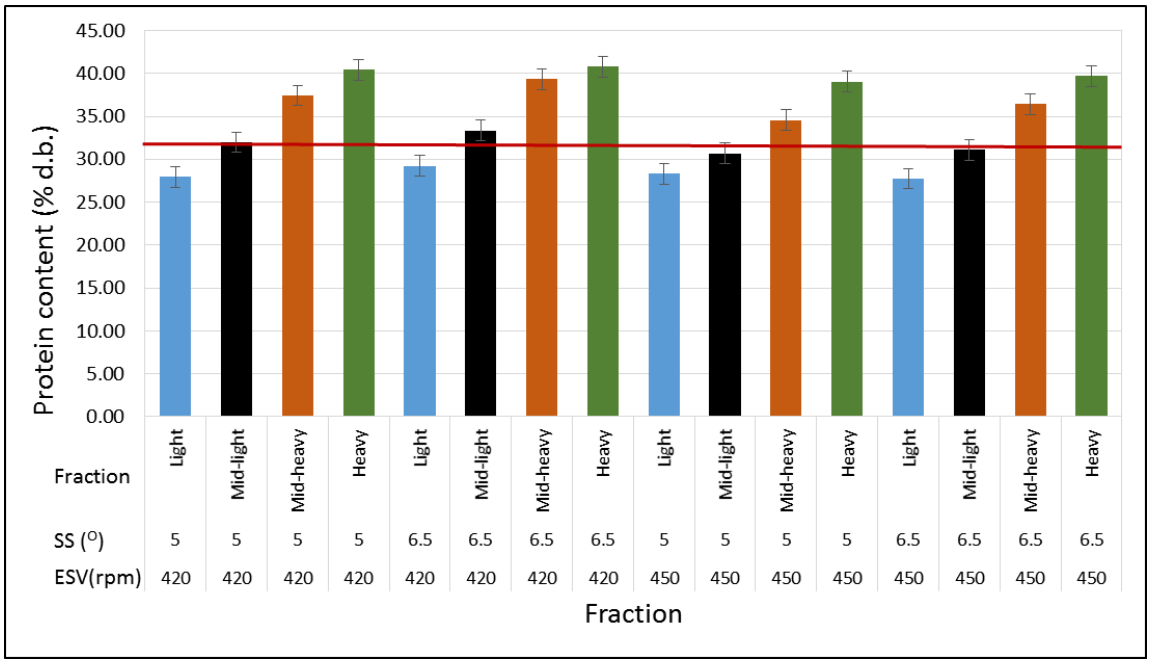

Figure 3.13. Protein content for raw DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

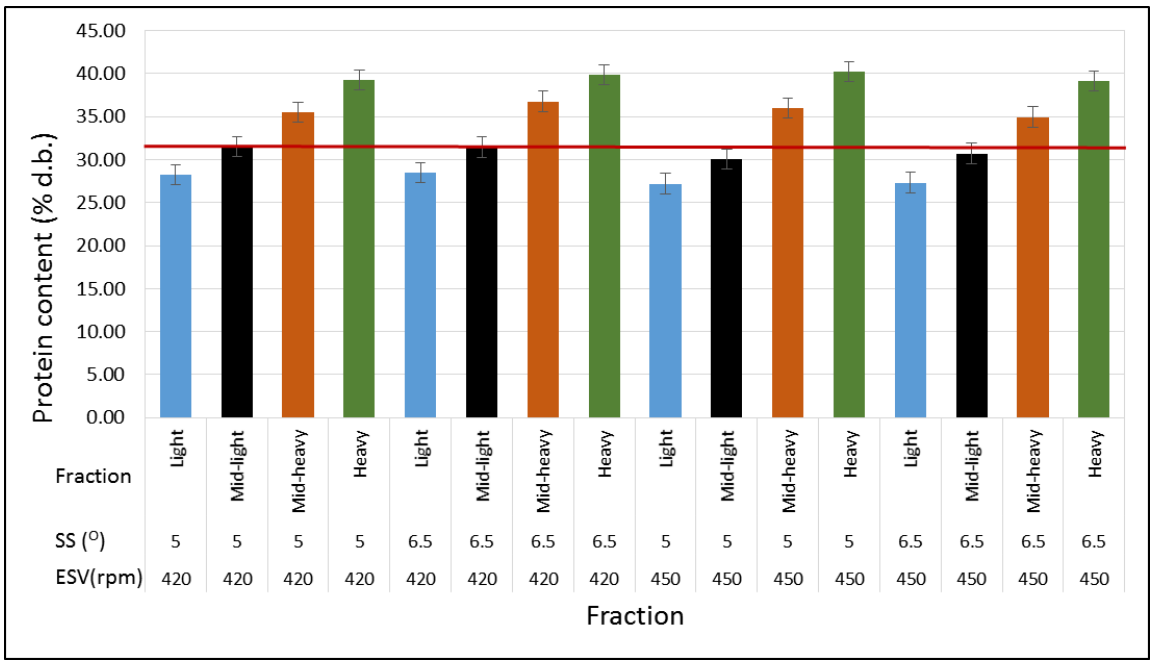

Figure 3.14. Protein content for 0.425-2.000 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

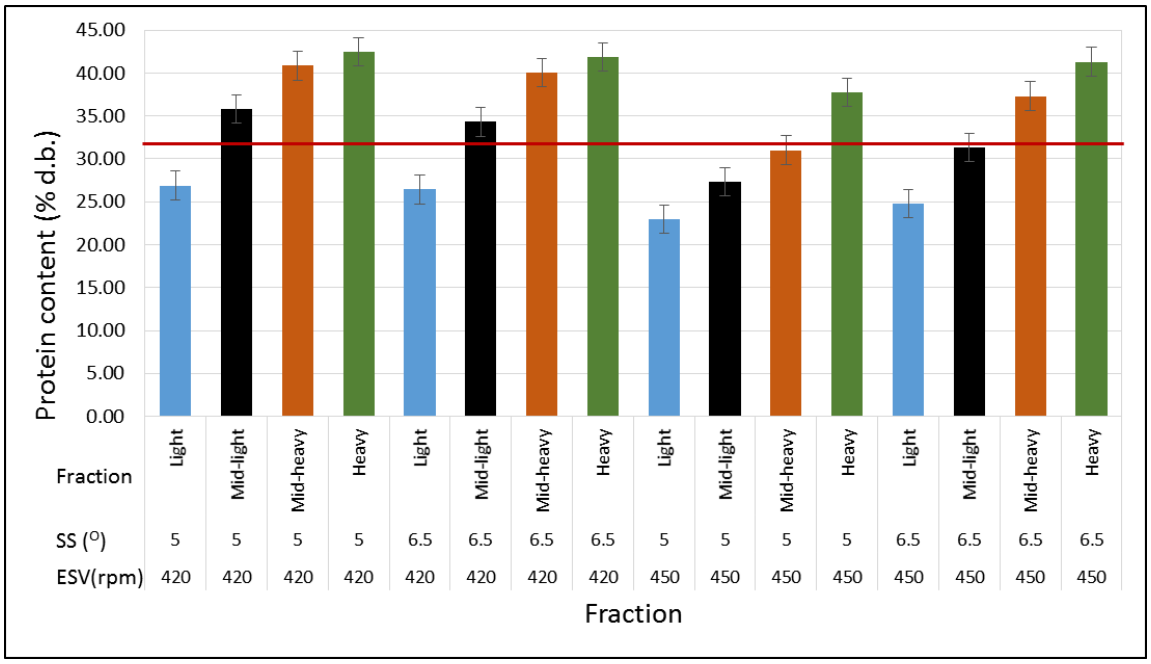

Figure 3.15. Protein content for 0.850-2.000 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

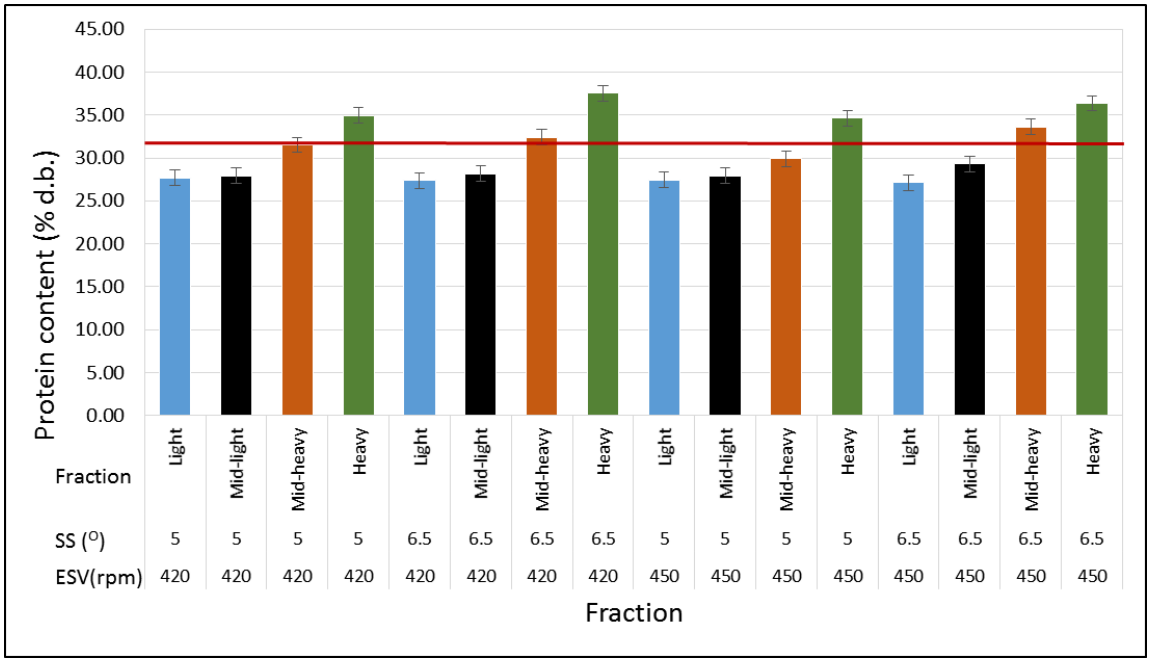

Figure 3.16. Protein content for 0.425-0.850 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

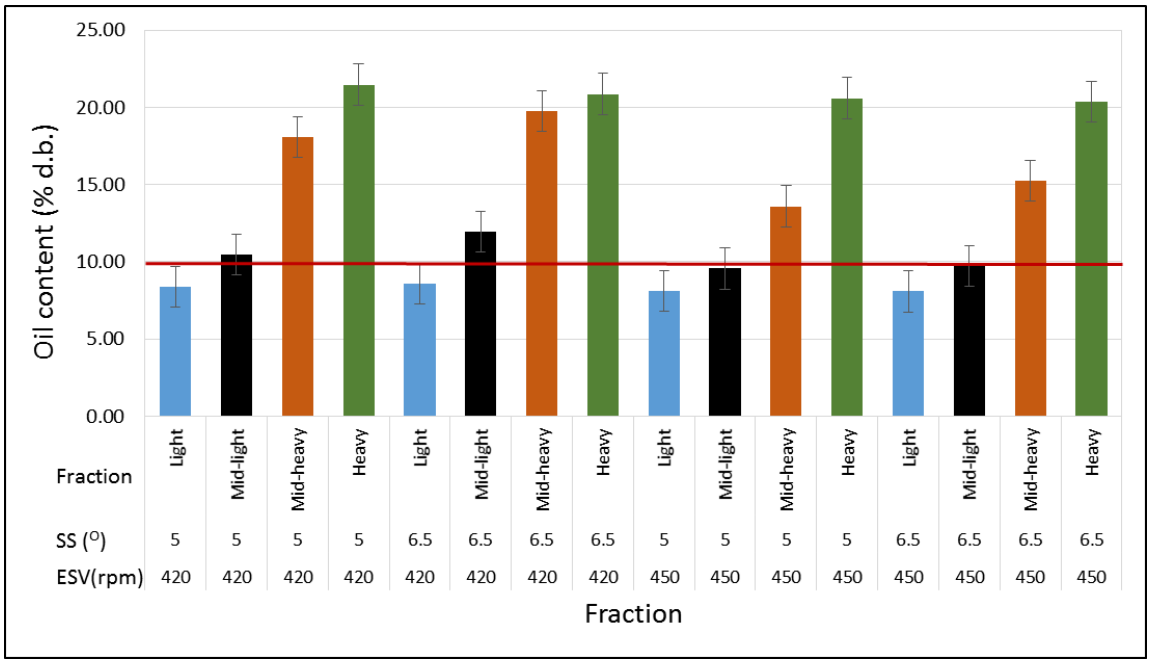

Figure 3. 17. Oil content for raw DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

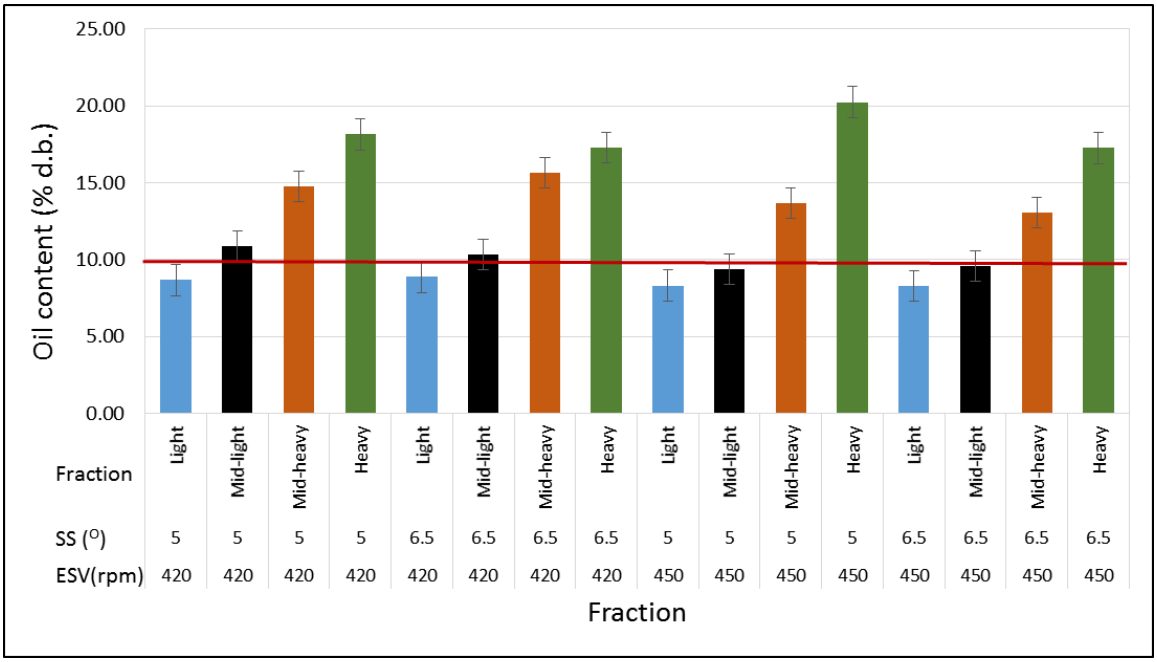

Figure 3.18. Oil content for 0.425-2.000 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

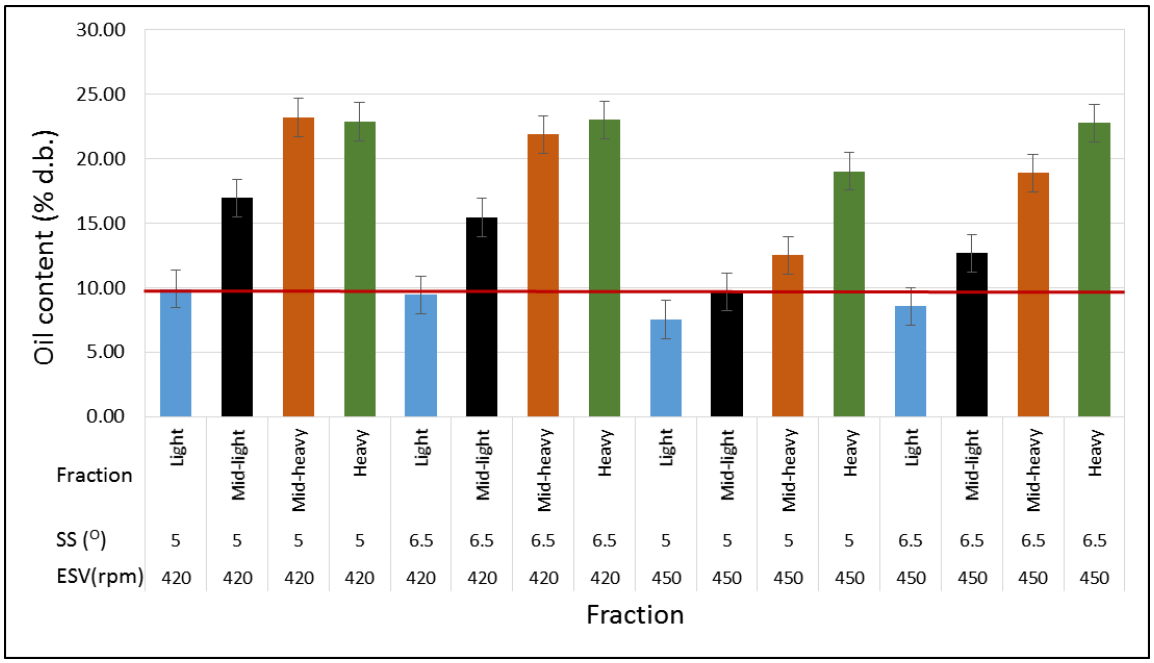

Figure 3.19. Oil content for 0.850-2.000 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

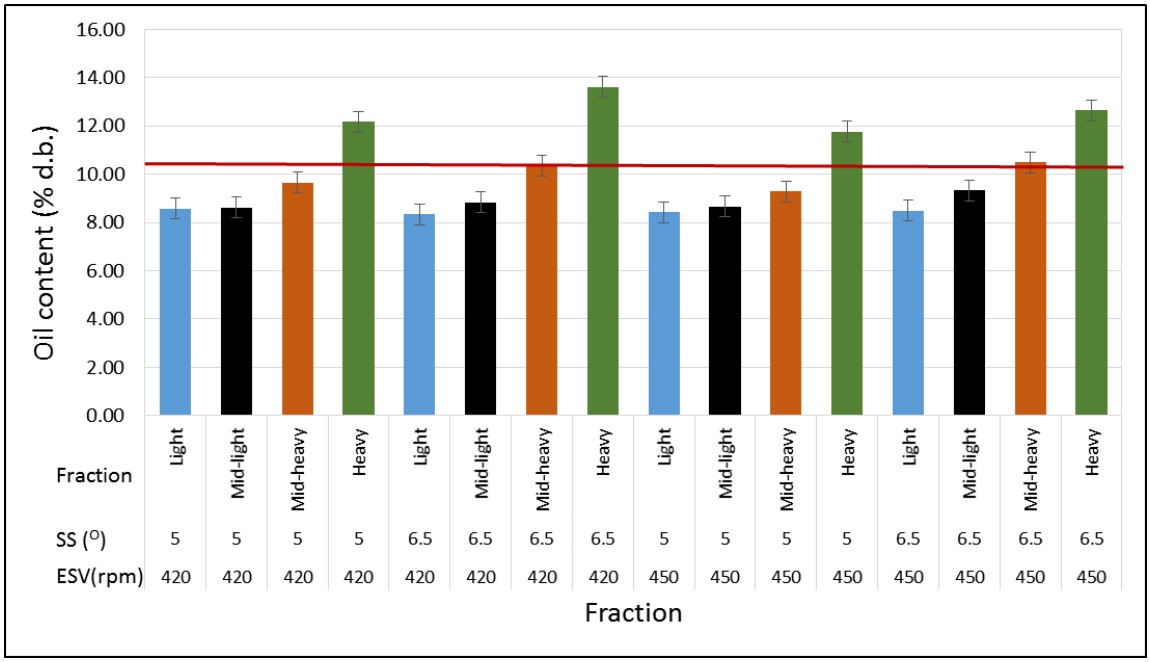

Figure 3.20. Oil content for 0.425-0.850 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

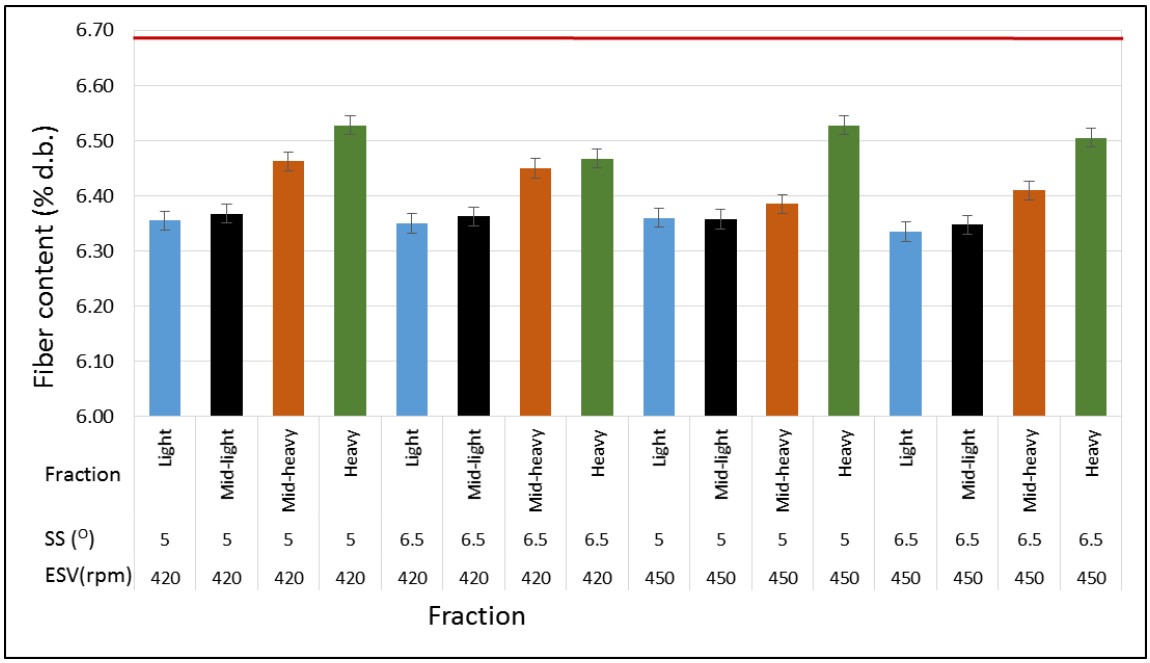

Figure 3.21. Fiber content for raw DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

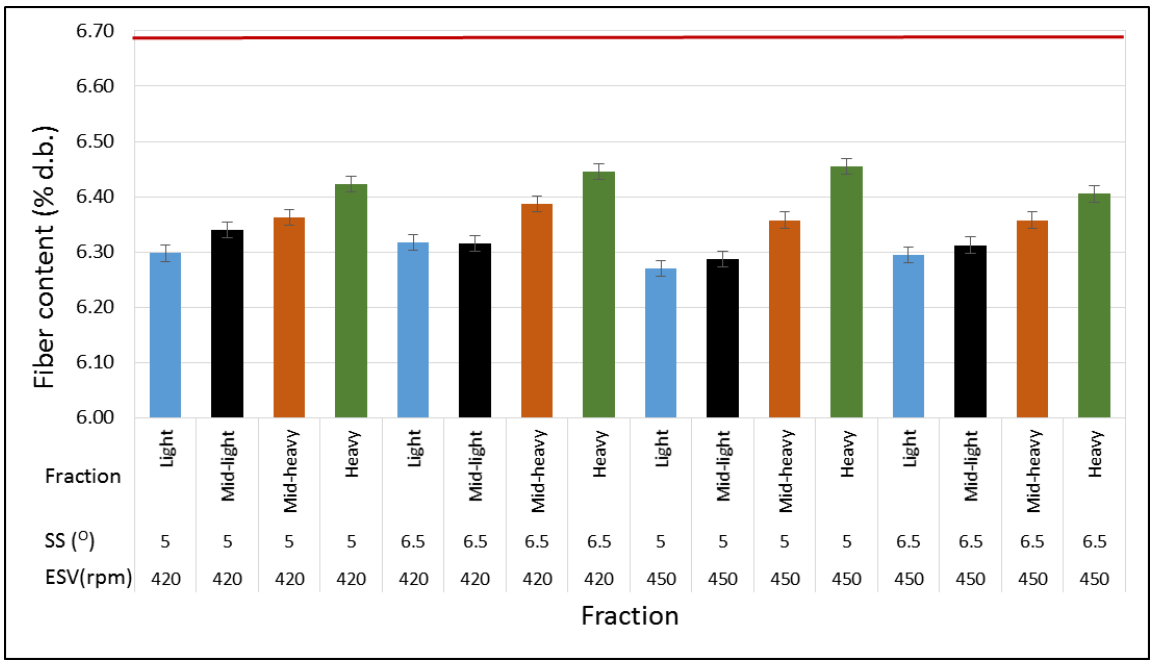

Figure 3.22. Fiber content for 0.425-2.000 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

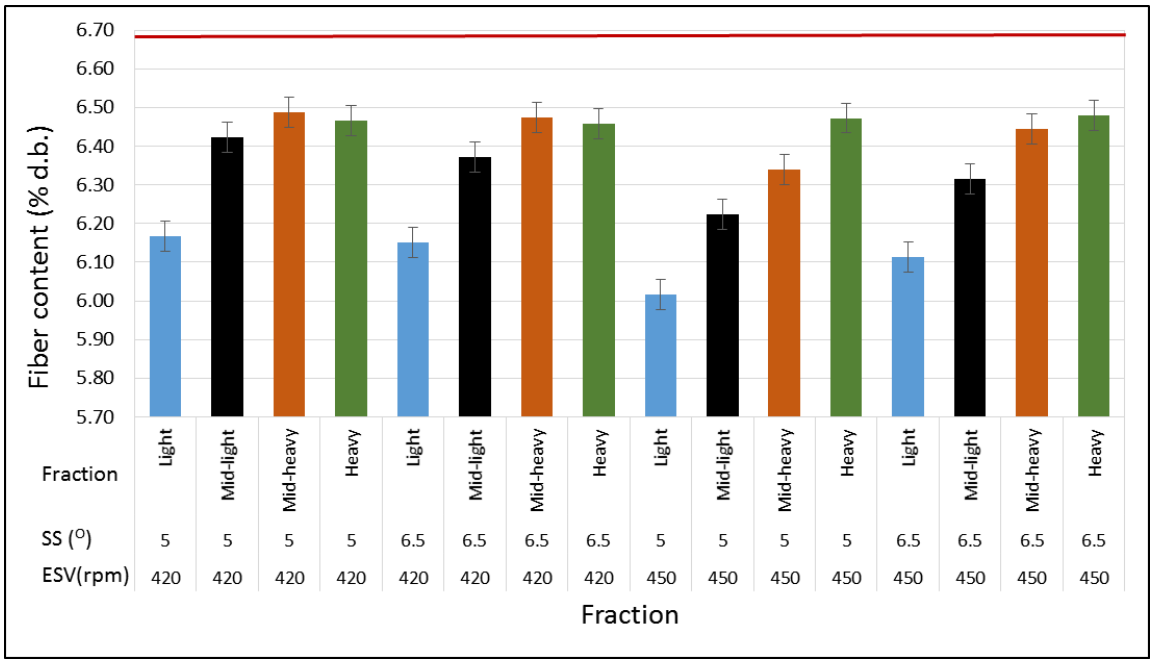

Figure 3.23. Fiber Percentage for 0.825-2.000 DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

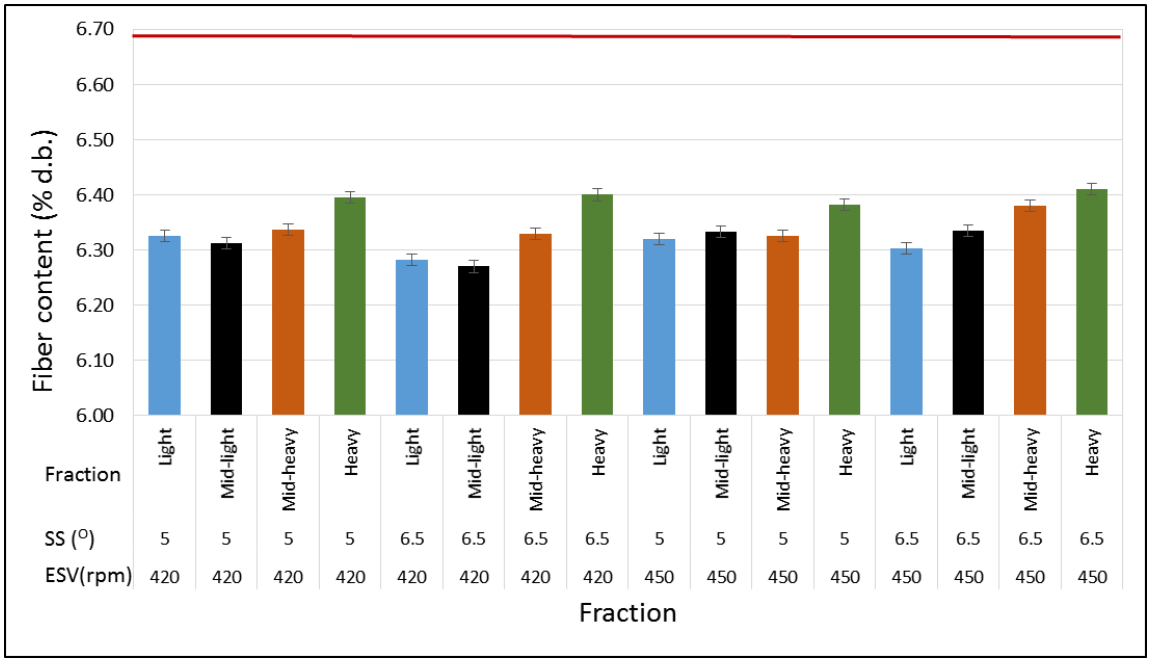

Figure 3.24 Fiber Percentage for 0.425-0.850 mm DDGS (Red line indicates level for raw DDGS, and error bars indicate standard error).

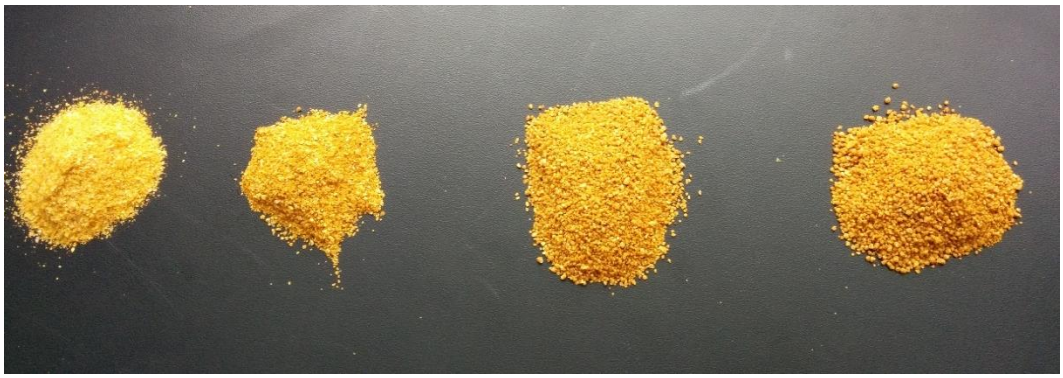

Figure 3.25 Four fractions from 0.425-2.000 mm DDGS after gravity separation under optimized parameters.

CHAPTER 4

FRACTIONATION OF DISTLLERS DRIED GRAINS WITH SOLUBLES (DDGS) THROUGH A GRAVITY SEPARATOR: LIFE CYCLE ASSESSMENT AND TECHNO-ECONOMIC ANALYASIS

This chapter is based on a manuscript to be submitted to *Industrial Crops and Products.*

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Abstract

Distillers dried grains with solubles (DDGS) are co-products of ethanol fermentation. DDGS could have higher market price and wider use if it could be separated into higher protein and higher fiber fractions. In our work, DDGS was firstly sieved into three size categories, and one category was further separated into light, mid-light, mid-heavy and heavy fractions using a gravity separator. This process was effective in getting enhanced DDGS with increased protein and oil. In this study, both Life cycle assessment (LCA) and Techno-economic analysis (TEA) of our approach to DDGS fractionation were conducted. Three scales, including lab scale, pilot scale, and commercial scale of DDGS fractionation were considered and analyzed. All equipment parameters were obtained from industrial manufacturers. Both the environmental impact and the cost per unit of DDGS fractionation decreased as the fractionation scale expanded. When the scale was large enough, such as with a processing rate of 864 t/y and above, DDGS fractionation was profitable.

Keywords

Distillers dried grains with solubles (DDGS), Fractionation, Gravity separator, Life cycle assessment (LCA), Techno-economic analysis (TEA).

4.1 Introduction

In 2012, biofuels contributed to 7.1% of total transport fuel consumption in the U.S., which was about 13.8 billion gallons (USDA, 2013). Ethanol was the most important biofuel in the U.S. and made up to 94% of all biofuel production in 2012 (USDA, 2013). In the U.S., ethanol is mostly made from corn. Corn kernels are fermented and then separated, and will produce the main product—ethanol, as well as different wet and dried distillers grains co-products, including DDGS (USGC, 2012).

Distillers dried grains with solubles (DDGS) are co-products of ethanol fermentation. DDGS includes protein, oil, fiber, and ash (Rosentrater and Muthukumarappan, 2006). DDGS can be widely used as feed ingredients for animals, such as fish, cattle, swine and poultry. However, use can be limited due to high fiber contents and not all animals have the ability to digest fiber.

Typically DDGS contains around 29% protein, 10% fat, 9% crude fiber and 5% ash (Lim et al, 2008). In the marketing year 2012-2013, DDGS was sold between average prices of $229.00-285.50 (USDA, 2014). According to Belyea et al, (2004), the price of DDGS with high oil (13%) and high protein (33%) contents costs about $5–20 more per ton than regular DDGS. It was estimated that about 38.95 million tonnes of DDGS were produced during the crop year 2013-2014 (AGMRC, 2014). The marketing potential is promising if we can produce DDGS with high protein content. Life cycle assessment (LCA) is an approach of assessing environmental impacts of a product or service during its cradle to grave lifetime. The environmental impact of each functional unit is the variable we concern. LCA provides environmental performance information that can be used in the comparison of products with equivalent functions, or in the determination of life cycle

impacts that are important to the overall environmental impact (Robert et al., 2002). LCA is a decision-supporting tool when considering environmental management or making policies (Kodera, 2007).

Similarly, Techno-economic analysis (TEA) is an approach to assess technology and economic effects of a product or service during its cradle to grave lifetime. The overall cost and cost per functional unit are the variables of concern. TEA, to some extent, plays an even more critical role during manufacturing decisions than LCA due to its direct relationship to cost and profit.

4.2 Methodology

In our study, DDGS fractionation was conducted with a sifter and a gravity separator. DDGS was firstly sieved into three size categories: >2.000 mm (over 10 mesh), 0.425-2.000 mm (10-40 mesh), and <0.425 mm (through 40 mesh); and then one category of 0.425-2.000 mm DDGS was further separated into light, mid-light, mid-heavy, and heavy fractions using a gravity separator. In this paper, we conducted both Life cycle assessment (LCA) and Techno-economic analysis (TEA) for this approach to fractionation. We evaluated both the environmental impacts, as well as economics of DDGS fractionation. Three scales of DDGS fractionation, including lab scale, pilot scale, and commercial scale, were considered and analyzed.

The analysis was based on the assumption that an ethanol plant conducted the fractionation so the cost of raw DDGS was negligible.

4.2.1. System Boundary and Fractionation Flowchart

Since the study was based on the assumption that an existing ethanol plant would fractionate DDGS and sell it as a co-product, the system boundaries had to adapt to this purpose. In this study we only considered LCA and TEA within the two processes of DDGS sieving and gravity separation. The system boundary and flowchart were shown in Figure 4.1 and Figure 4.2.

4.2.2 Functional Unit

We conducted both TEA and LCA based on a functional unit of 1 tonne DDGS. We analyzed annual total impacts and impacts per tonne of DDGS.

4.2.3. Main Assumptions

4.2.3.1. Main assumptions for lab scale

In the lab scale, one sifter (Sweco LS18_333) was used to sieve the DDGS and one gravity separator (Forsberg TKV 25) was used for gravity separation. Two feeders (Vibra Screw Feeder 2" AccuFeed) were required, one for the sifter and one for the gravity separator.

4.2.3.2. Main assumptions for pilot scale

In the pilot scale, one sifter (Sweco MX40S666) was used to sieve the DDGS and one gravity separator (Forsberg TKV 2000) was used for gravity separation. Two feeders (Vibra Screw Feeder 4" AccuFeed) were required, one for the sifter and one for the gravity separator.

4.2.3.3. Main assumptions for commercial scale

In the commercial scale, five sifters (Sweco MX60S888) were used to sieve DDGS and thirty four gravity separators (Forsberg TKV 2000) were used for gravity separation.

Two models of feeders (Vibra Screw Feeder 4" AccuFeed and Vibra Screw Feeder 8" HD Feeder) were required, five of 8" HD Feeder for each sifter and thirty four of 4" AccuFeed for each gravity separator.

4.2.4. Assumptions for LCA

(1) The environmental impacts we considered contained energy use and air emissions. The electricity loss during transportation was negligible. Based on our experiments, electricity was the only energy consumed, and no water or fuel needed to be considered. The three air emission categories we considered were carbon dioxide, methane, and NO_x.

(2) The electricity came from a coal-fired plant. The air emissions of producing electricity from coal were shown in Table 4.1 (Spath et al., 1999).

4.2.5. Assumptions for TEA

(1) Based on our experiments, after sieving using the sifter, the weight of over 10 mesh (>2.000 mm) DDGS accounted for 4.54%, 10--40 mesh (0.425--2.00 mm) DDGS accounted for 86.98%, and through 40 mesh (<0.425 mm) accounted for 8.48%. After gravity separation, the protein percentage and mass percentage for each fraction were shown in Table 4.2.

(2) The capacity of the sifter Model Sweco LS18_333 was 30 kg/h, the capacity of the sifter Model Sweco MX40S666 was 300 kg/h, and the capacity of the sifter Model Sweco MX60S888 was 3,000 kg/h.

(3) The capacity of the gravity separator Model TKV25 was 40 kg/h, while the capacity of the larger gravity separator Model TKV2000 was 400 kg/h.

(4) In lab scale and pilot scale, 1 sifter and 1 gravity separator were required; while in commercial scale, 5 sifters and 34 gravity separators were required. The equipment model and number for three scales were shown in Table 4.3.

(5) The screens had to be replaced every 2 months, so the required number of screens for one sifter was 12 per year.

(6) The filter had to be replaced every 2 months, so the required number of filter for one gravity separator was 6 per year.

(7) The feeding rate for sieving was fundamental for operating hours. In the lab and pilot scales, sifters were run 8 hours per day, and 360 days per year. In the commercial scale, 5 sifters were supposed to work 24 hours per day and 365 days per year.

(8) The price of electricity was $0.09/kWh, the yearly interest rate was 5.5%, the insurance rate was 0.462%, the hourly salary was $12/h, and equipment maintenance was $1/t.

(9) The life span of the equipment was 10 years, except filters and screens. All equipment prices came from manufacturers except filters. Due to the large scale of separation in the commercial scale, the equipment could be bought at 85% of the original price.

(10) Since DDGS price varied as economic situation varied, the fractionated DDGS could be assumed selling at prices of $5, $8, and $15/percent of protein. As a result, based on the information in Table 4.2, the DDGS price could be $168.95/t, $270.31/t, and $506.84/t, respectively. The loss of DDGS during fractionation is negligible.

(11) The depreciation and salvage value at the end of service life are assumed to be 0.

4.3 Results and Discussion

All of the annual environmental impact categories increased as the scale expanded, while all of the unit environmental impact categories decreased as the scale expanded. The details were shown in Table 4.4 and Figures 4.3-4.10. In Figures 4.3, 4.5, 4.7, and 4.9, the relationship of annual environmental impacts and DDGS fractionation capacity could be regressed as both linear and exponential trend lines, and both those two type regressions had reasonable R^2. In industry, the shaded region referred to the flexibility caused by different fractionation efficiency, such as the variance of DDGS samples, variance of DDGS feeding rate, variance of equipment performance, etc.

The comprehensive cost determined by TEA was shown in Table 4.5. For each scale, the annualized cost was considered including capital cost and operating cost, and the details were shown in Tables 4.6-4.11. The annualized total cost increased as the scale expanded, and the trend lines could be regressed as both linear and exponential trend lines, and both those two type regressions had R^2 that equaled or closed to 1. The shaded region referred to the flexibility caused by different fractionation efficiency. The details were shown in Figure 4.11. The unit cost was considered on the base of per tonne DDGS and decreased as the scale expanded, and the details was shown in Figure 4.12.

The annual and unit profits of DDGS fractionation with various DDGS prices were shown in Tables 4.12 and 4.13. When DDGS fractionation capacity was 86.4 t/y, both annual and unit profits were negative with three DDGS prices. When DDGS fractionation capacity was 864 t/y and 131,400 t/y, both annual and unit profits were positive with three DDGS prices. The regression trend lines for annual and unit profits of DDGS fractionation with various DDGS prices were shown in Figures 4.13 and 4.14.

Based on current knowledge, the present work was the only LCA and TEA analysis conducted for DDGS fractionation. All the study was based on the optimized parameters of sifter and gravity separator. The results showed that the unit environmental impacts decreased as DDGS fractionation scale expanded, which indicated that it was proper for commercial scale to separate DDGS; while for small scales, gathering DDGS from different plants and fractionating them together could be an alternative way.

The results also showed that DDGS fractionation through a gravity separator was profitable when it was operated in commercial scale, such as with a processing rate of 864 t/y and above, which was possible for medium size bio ethanol plant in the U.S. When this process was conducted in a lab scale, it was not possible to make profit due to limited working time and high cost of labor. Various DDGS prices were also considered in this study, which might provide useful information when DDGS varied as marketing changed. There were various types of sifters and gravity separators, future work will explore other costless machines.

4.4 Conclusions

Based on our LCA and TEA analyses, both the environmental impact and the cost per unit of DDGS fractionation decreased as the fractionation scale expanded. This study provided useful information for DDGS fractionation at different scales with various prices. The results indicated that when the scale was large enough, such as with a processing rate of 864 t/y and above, DDGS fractionation was profitable.

Based on our DDGS fractionation optimized process through two screens and a gravity separator, it was a potential way to make profit for commercial-scale bio ethanol

plant to fractionate DDGS. In the lab scale, such as with a processing rate of 86.4 t/y and below, DDGS fractionation through this process was non-profitable, and the unit environmental burden was higher than commercial scale.

The future work will focus on evaluating DDGS fractionation processes through different sifters and gravity separators and explore other DDGS fractionation process, to prompt DDGS fractionation in industry.

4.5 Acknowledgement

The author would like to thank Mr. Alan Gaul and Dr. Hui Wang for their technical assistance; and thank Lincolnway Energy, LLC; Forsberg, Inc.; Sweco, LLC; and Vibra Screw, Inc., for their price inquiry assistance.

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Table 4.1. Air emission of producing electricity from coal.

Emission category	g/kWh
CO_2	1,022[a]
CH_4	0.91[a]
NO_x	3.35[a]

a: Spath, P. L., Mann, M. K., and Kerr, D. R.. (1999). Environmental Aspects of Producing Electricity from a Coal-Fired Power Generation System-A Life Cycle Assessment. National Renewable Energy Laboratory, USA.

Table 4.2. DDGS price after gravity separation based on various prices per percent protein.

Size Category	Fraction	Protein	Mass Percentage	Price ($)		
(mm)		(% d.b.)	(%)	$5/ PP	$8/ PP	$15/ PP
0.425-2.000	Light	28.27	23.45	34.71	43.99	104.14
	Midlight	31.54	26.71	33.99	79.58	101.98
	Midheavy	35.52	19.14	49.74	54.39	149.22
	Heavy	39.27	17.68	27.50	55.54	82.49
>2.000	NA	37.05	4.54	8.41	13.46	25.23
<0.425	NA	34.42	8.48	14.59	23.35	43.78
Raw	NA	32.13	100.00	168.95	270.31	506.84

*Price was calculated on the base of $8/percent of protein. NA is not available. PP is percent protein.

Table 4.3. Equipment information for DDGS fractionation.

Scale		Lab	Pilot	Commercial
Capacity	(t/y)	86.4	864	131,400
	(kg/h)	30	300	15,000
Sifter	(Model)	Sweco LS18_333	Sweco MX40S666	Sweco MX60S888
	(No.)	1	1	5
Gravity Separator	(Model)	Forsberg TKV 25	Forsberg TKV 2000	Forsberg TKV 2000
	(No.)	1	1	34

Table 4.4. Life cycle assessment for DDGS fractionation.

Processing ate (t/y)	**86.4**		**864**		**131,400**	
Environmental impact	Total annual impact (per year)	Unit impact (per tonne per year)	Total annual impact (per year)	Unit impact (per tonne per year)	Total annual impact (per year)	Unit impact (per tonne per year)
Electricity use (kWh)	16,107.12	186.43	45,811.33	53.02	6,540,497.42	49.78
CO_2 emission (kg CO_2)	16,461.48	190.53	46,819.18	54.19	6,684,388.36	50.87
CH_4 emission (g CH_4)	14,657.48	169.65	41,688.31	48.25	5,951,825.65	45.30
NO_x emission (g NO_x)	53,958.85	624.52	153,467.97	177.62	21,910,666.34	166.75

Table 4.5. Annualized total cost and unit cost of DDGS fractionation.

Scale	Capacity (kg/h)	Total separation weight (t/y)	Total costs ($/year)	Unit costs ($/t)
Lab	30	86.4	74,432.67	861.49
Pilot	300	864	96,001.15	111.11
Commercial	15,000	131,400	1,674,075.34	12.74

Table 4.6. Lab scale capital costs of DDGS fractionation (30 kg/h).

Component	Type	Price ($/each)	Quantity	Total Cost ($)
Feeder	Vibra screw feeder 2" AccuFeed	4,000.00	2	8,000.00
Sifter	Sweco LS18_333	6,696.00	1	6,696.00
Gravity separator	Forsberg TKV25	14,454.00	1	14,454.00
Fan	Forsberg Model 12-HA	3,379.00	1	3,379.00
Cyclone	Forsberg 33” HE	7,467.00	1	7,467.00
Equipment initial Costs ($)				**39,996.00**
Electrical wiring and controls				1,599.84
Equipment installation				15,998.40
Equipment freight				399.96
Total equipment initial costs ($)				**57,994.20**
Engineering and design				2,911.71
Total capital costs ($)				**60,905.91**
Capital costs per year ($)				**8,080.25**

Table 4.7. Lab scale operating costs of DDGS fractionation (30 kg/h).

Component	Total cost ($/year)
Fixed costs	
Interest	3,349.82
Insurance	281.39
Tax	213.17
Subtotal ($/year)	**3,844.38**
Variable costs	
Screen	1,884.00
Filter	1,200.00
Electricity	1,449.64
Labor	57,888.00
Maintenance and repair	86.40
Subtotal ($/year)	**62,508.04**
Total costs ($/year)	**66,352.42**

Table 4.8. Pilot scale capital costs of DDGS fractionation (300 kg/h).

Component	Type	Price ($/each)	Quantity	Total Cost ($)
Feeder	Vibra Screw Feeder 4" AccuFeed	4,100.00	2	8,200.00
Sifter	Sweco MX40S666	11,346.00	1	11,346.00
Gravity separator	Forsberg TKV2000	51,249.00	1	51,249.00
Fan	Forsberg Model 21-HA	7,882.00	1	7,882.00
Cyclone	Forsberg 74” HE	15,083.00	1	15,083.00
Equipment initial costs ($)				**93,760.00**
Electrical wiring and controls				3,750.40
Equipment installation				37,504.00
Equipment freight				937.60
Total equipment initial costs ($)				**135,952.00**
Engineering and design				6,825.73
Total capital costs ($)				**142,777.73**
Capital costs per year ($)				**18,942.00**

Table 4.9. Pilot scale operating costs of DDGS fractionation (300 kg/h).

Component	Total cost ($/year)
Fixed costs	
Interest	7,852.78
Insurance	659.63
Tax	499.72
Subtotal ($/year)	**9,012.13**
Variable costs	
Screen	3,072.00
Filter	2,100.00
Electricity	4,123.02
Labor	57,888.00
Maintenance and repair	864.00
Subtotal ($/year)	**68,047.02**
Total costs ($/year)	**77,059.15**

Table 4.10. Commercial scale capital cost of DDGS fractionation (15,000 kg/h).

Component	Type	Price ($/each)	Quantity	Total cost ($)
Feeder	Vibra Screw Feeder 4" AccuFeed	3485.00	34	118490.00
	Vibra Screw Feeder 8" HD	7,709.50	5	38,547.50
Sifter	Sweco MX40S666	18,045.75	5	90,228.75
GravitysSeparator	Forsberg TKV2000	38,436.75	34	1,306,849.50
Fan	Forsberg Model 21-HA	5,911.50	34	200,991.00
Cyclone	Forsberg 74” HE	11,312.25	34	384,616.50
Equipment initial costs ($)				**2,139,723.25**
Electrical wiring and controls				85,588.93
Equipment installation				855,889.30
Equipment freight				21,397.23
Total equipment initial costs ($)				**3,102,598.71**
Engineering and design				155,771.85
Total capital costs ($)				**3,258,370.57**
Capital costs per year ($)				**432,280.75**

Table 4.11. Commercial scale operating costs of DDGS fractionation (15,000 kg/h).

Component	Total cost ($/year)
Fixed cost	
Interest	179,210.38
Insurance	15,053.67
Tax	11,404.30
Subtotal ($/year)	**205,668.35**
Variable cost	
Screen	19,560.00
Filter	71,400.00
Electricity	603,526.24
Labor	210,240.00
Maintenance and repair	131,400.00
Subtotal ($/year)	**1,036,126.24**
Total cost ($/year)	**1,241,794.59**

Table 4.12. Annual profit of DDGS fractionation at various DDGS prices.

Scale	Capacity (kg/h)	Total separation weight (t/y)	Annual profit ($/y) $168.95/t	$270.31/t	$506.84/t
Lab	30	86.4	-59,835.79	-51,077.65	-30,642.01
Pilot	300	864	49,967.72	137,549.04	341,905.47
Commercial	15,000	131,400	20,525,357.45	33,845,017.12	64,924,223.02

Table 4.13. Unit profit of DDGS fractionation at various DDGS prices.

Scale	Capacity (kg/h)	Total separation weight (t/y)	Unit profit ($/t) $168.95/t	$270.31/t	$506.84/t
Lab	30	86.4	-692.54	-591.18	-354.65
Pilot	300	864	57.83	159.20	395.72
Commercial	15,000	131,400	156.21	257.57	494.10

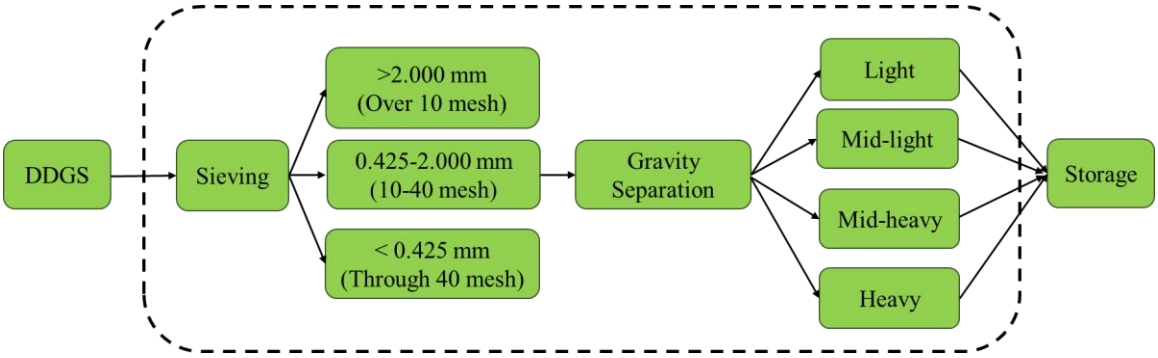

Figure 4.1. DDGS fractionation system boundary.

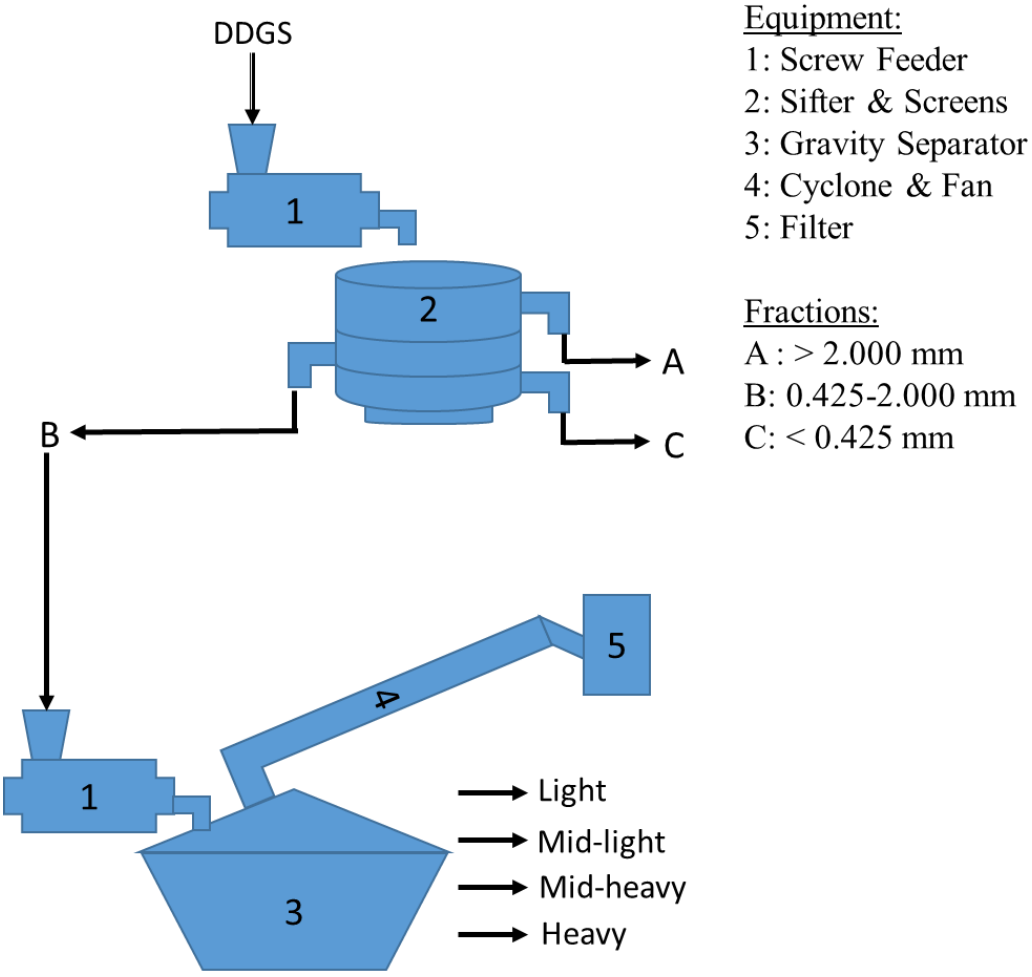

Figure 4.2. DDGS fractionation flowchart.

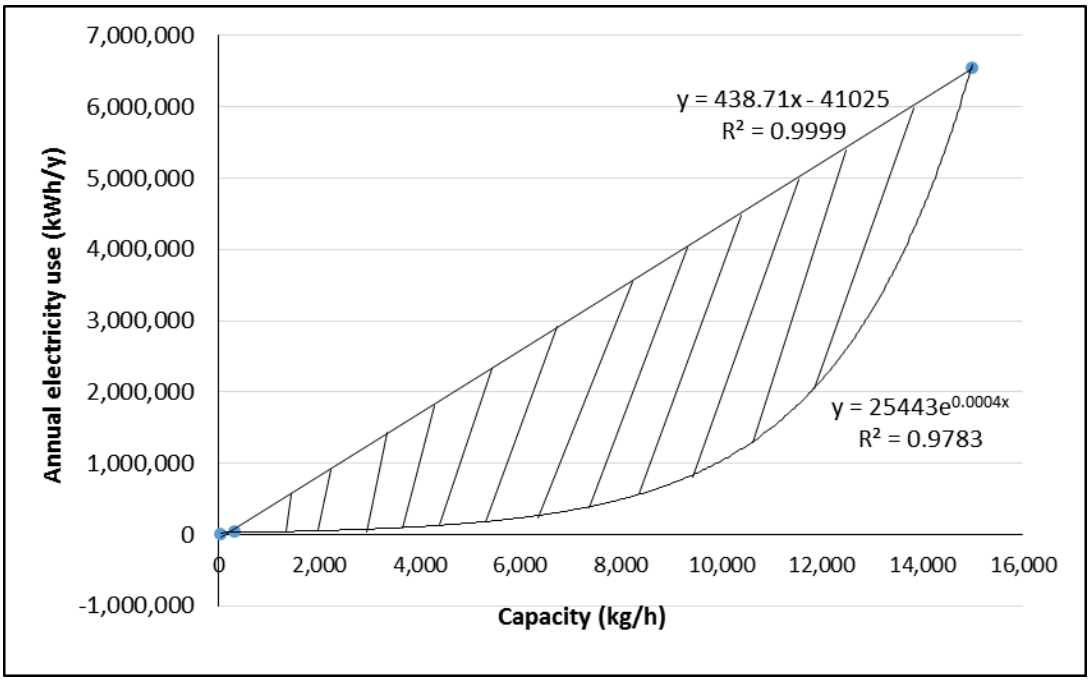

Figure 4.3. Annual electricity use of DDGS fractionation through a gravity separator (shaded region refers to the flexibility caused by different fractionation efficiency).

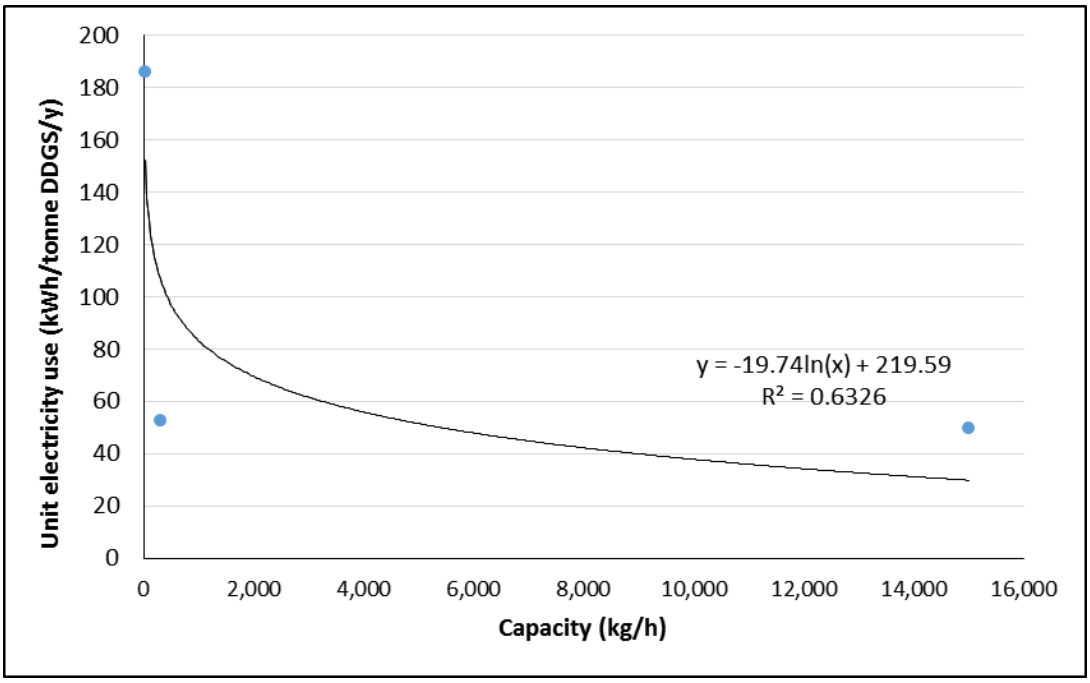

Figure 4.4. Unit electricity use of DDGS fractionation through a gravity separator.

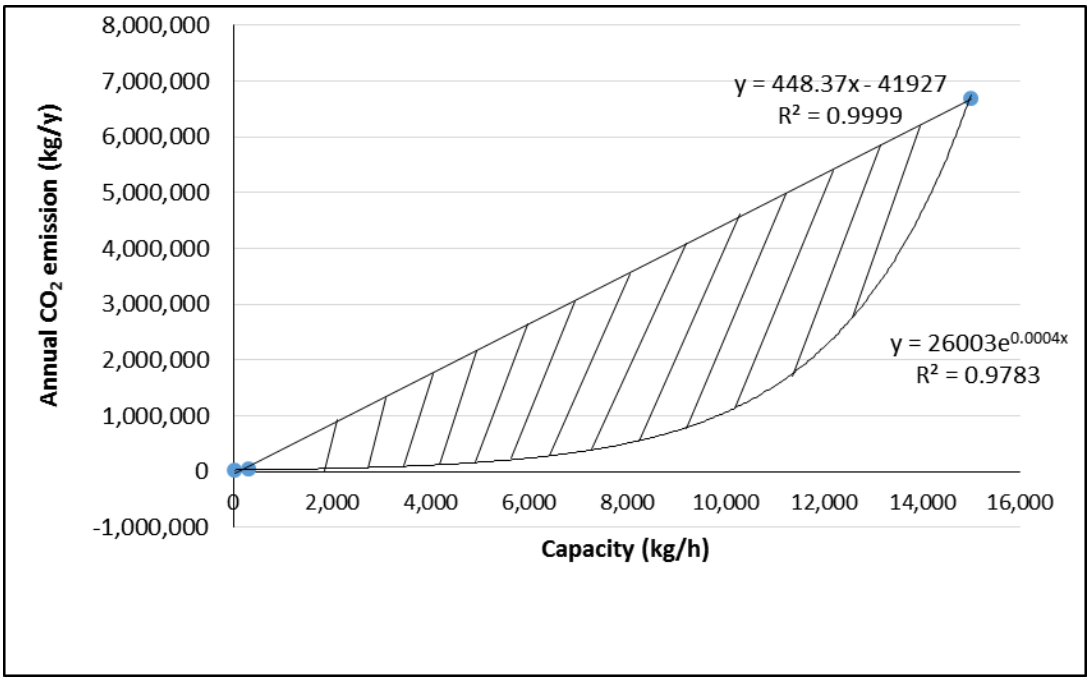

Figure 4.5. Annual CO_2 emission of DDGS fractionation through a gravity separator (shaded region refers to the flexibility caused by different fractionation efficiency).

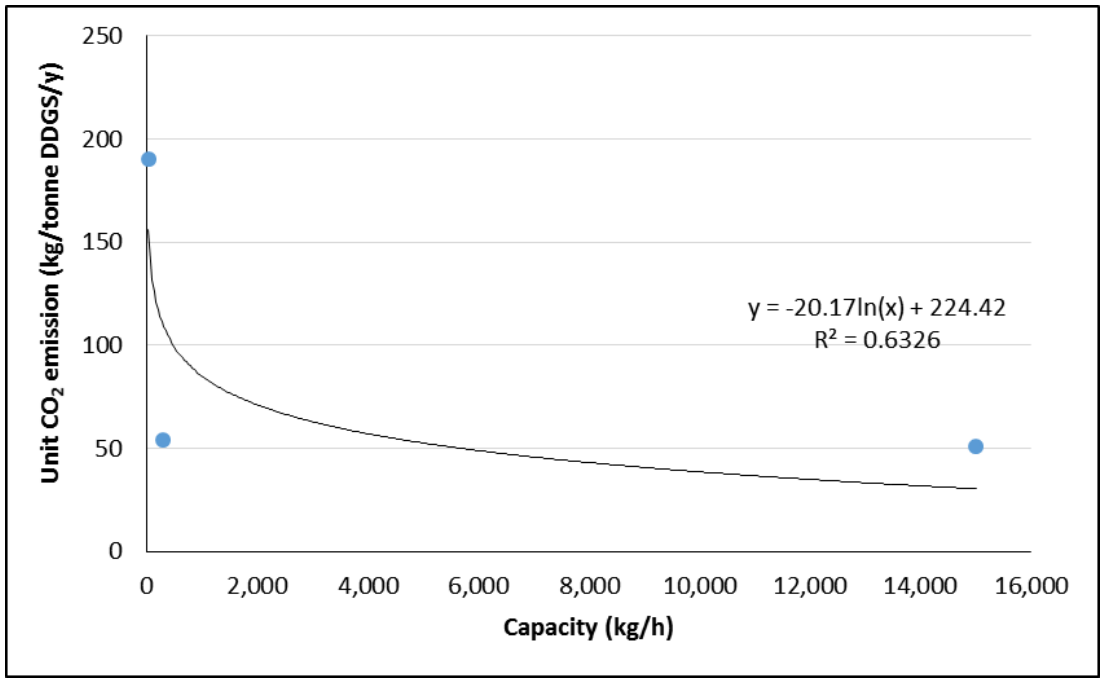

Figure 4.6. Unit CO_2 emission of DDGS fractionation through a gravity separator.

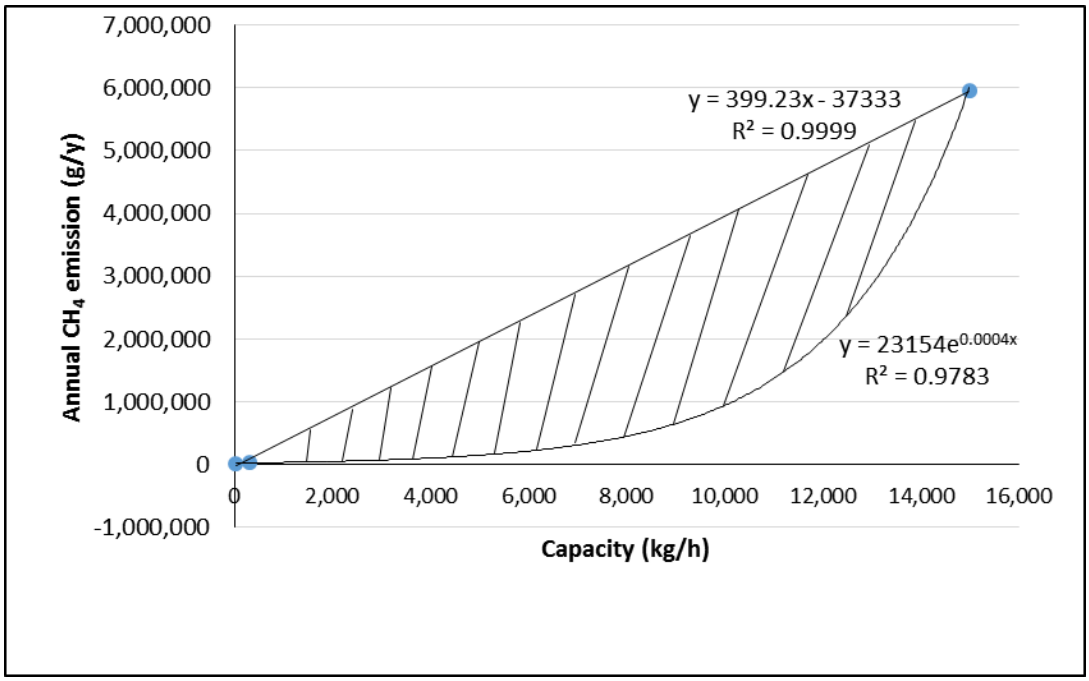

Figure 4.7. Annual CH_4 emission of DDGS fractionation through a gravity separator (shaded region refers to the flexibility caused by different fractionation efficiency).

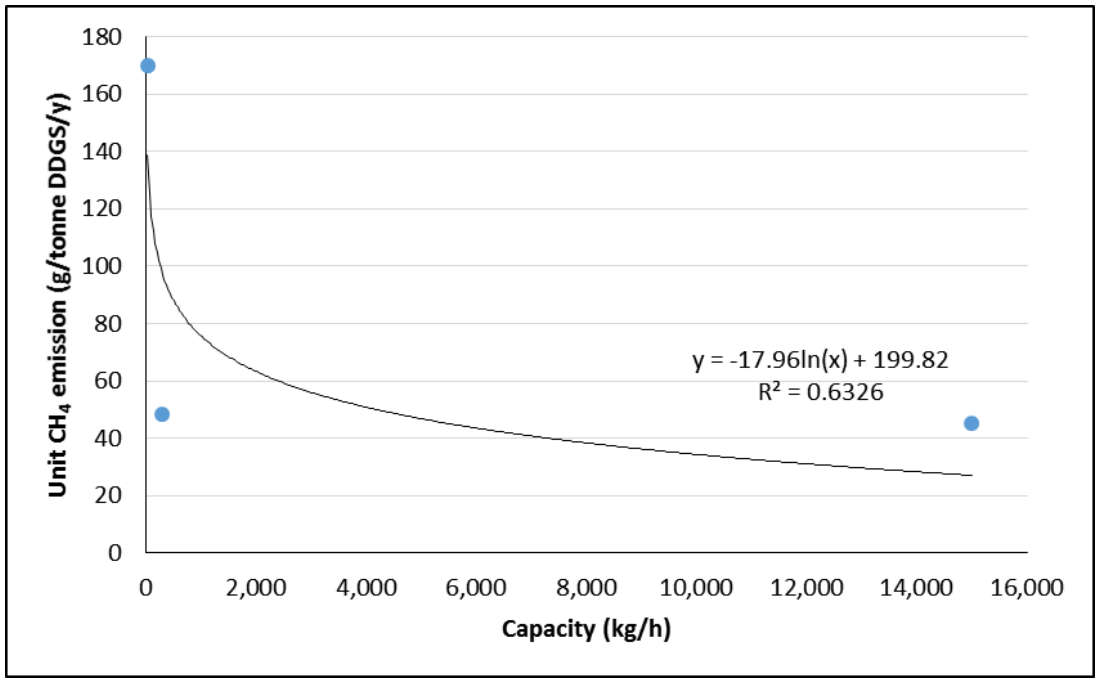

Figure 4.8. Unit CH_4 emission of DDGS fractionation through a gravity separator.

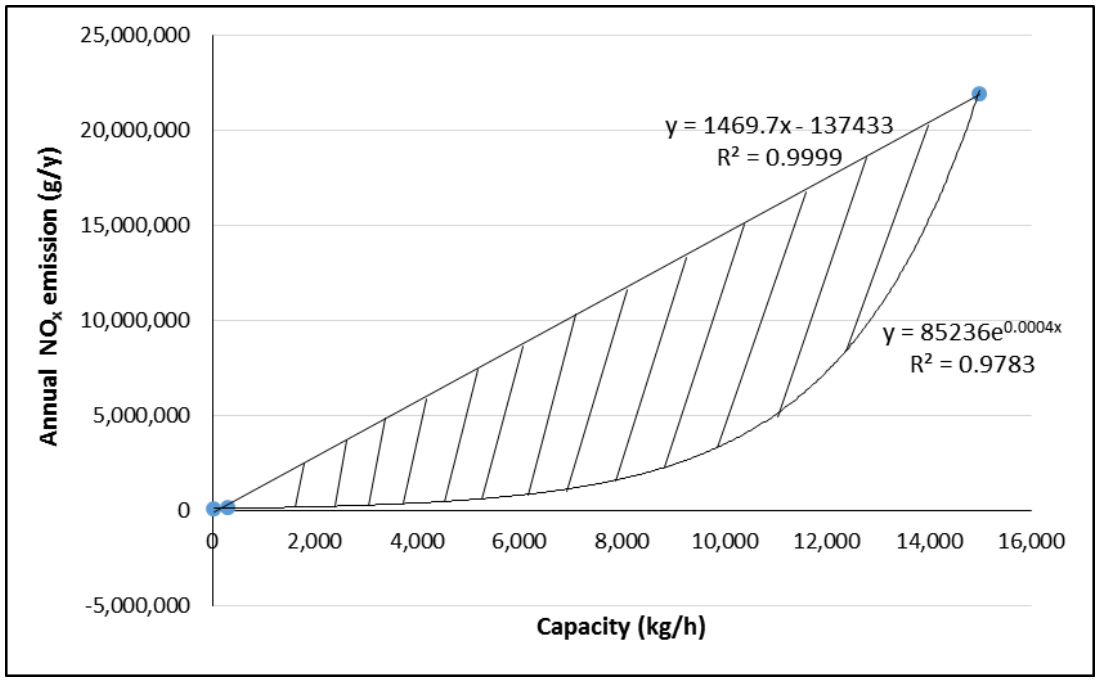

Figure 4.9. Annual NO_x emission of DDGS fractionation through a gravity separator (shaded region refers to the flexibility caused by different fractionation efficiency).

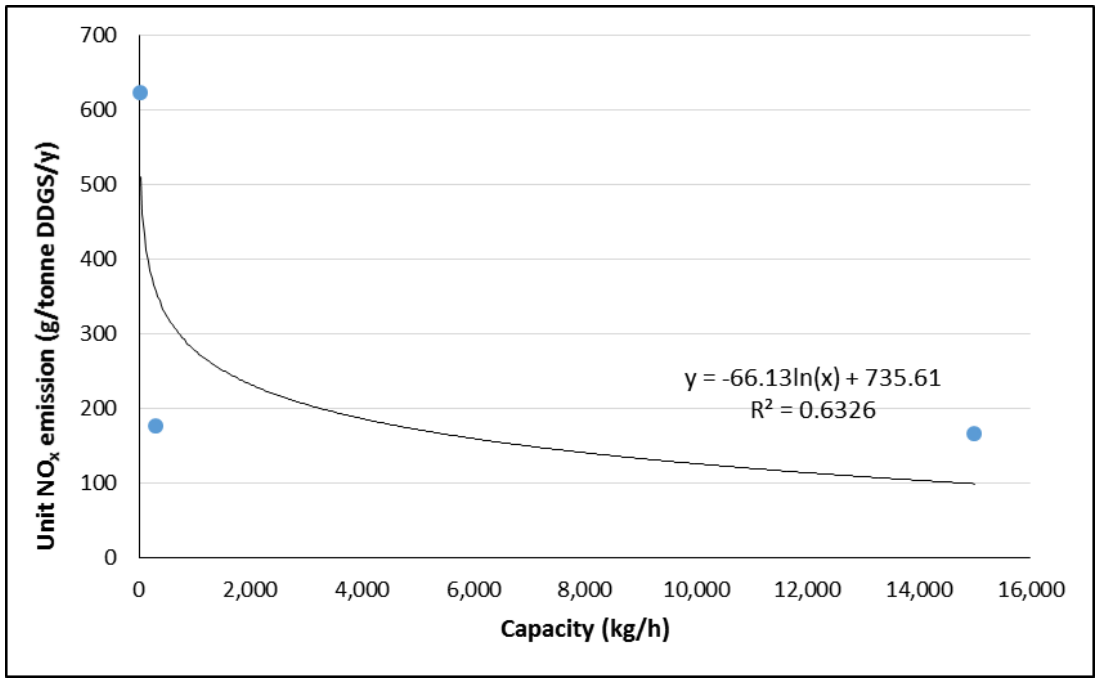

Figure 4.10. Unit NO_x emission as of DDGS fractionation through a gravity separator.

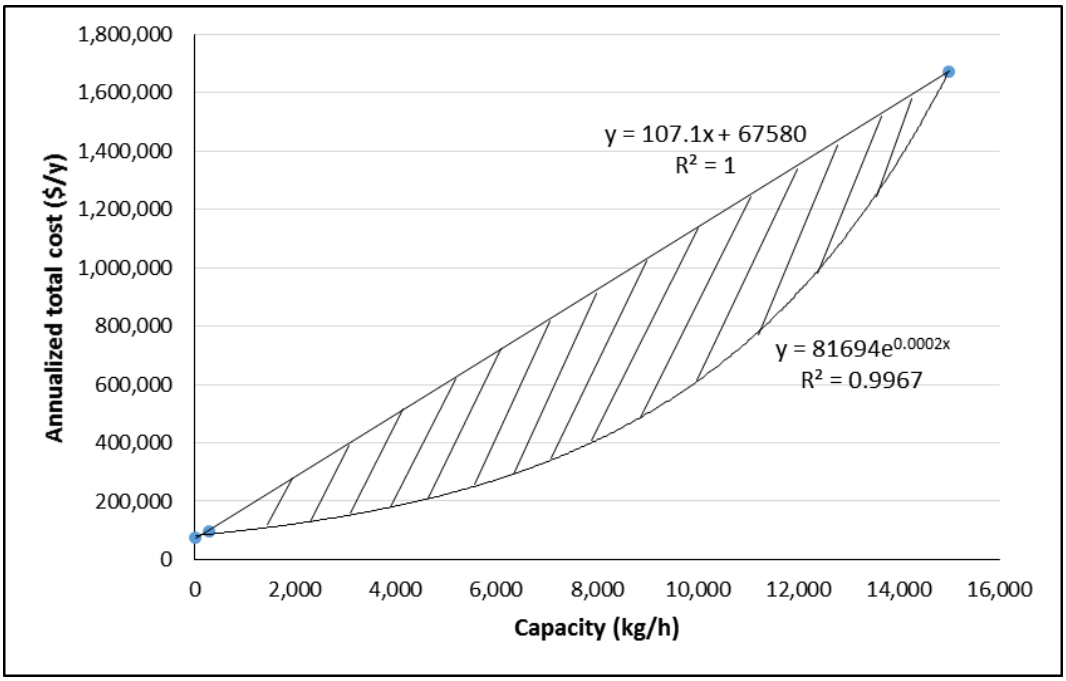

Figure 4.11. Annual cost of DDGS fractionation through a gravity separator (shaded region refers to the flexibility caused by different fractionation efficiency).

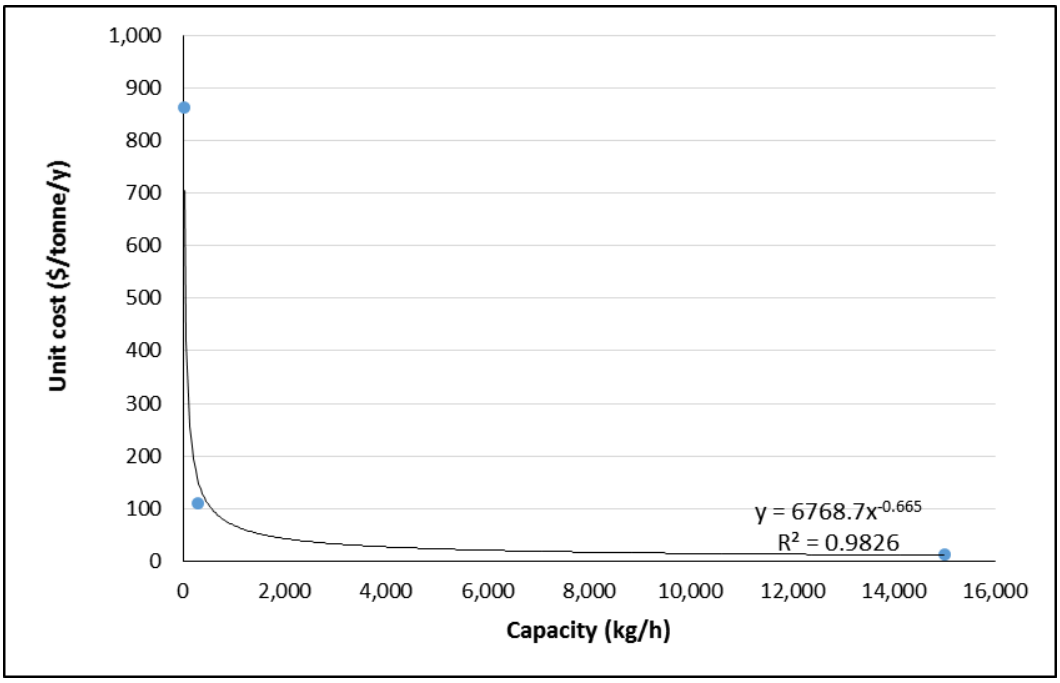

Figure 4.12. Unit cost of DDGS fractionation through a gravity separator.

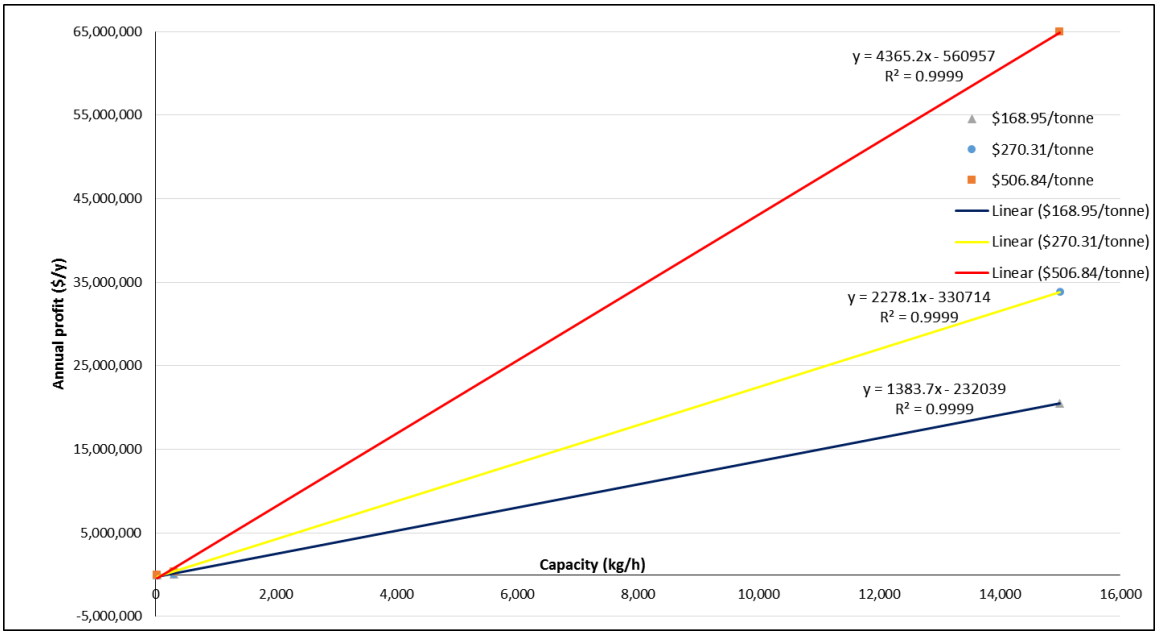

Figure 4.13. Annual profit of DDGS fractionation with various DDGS prices.

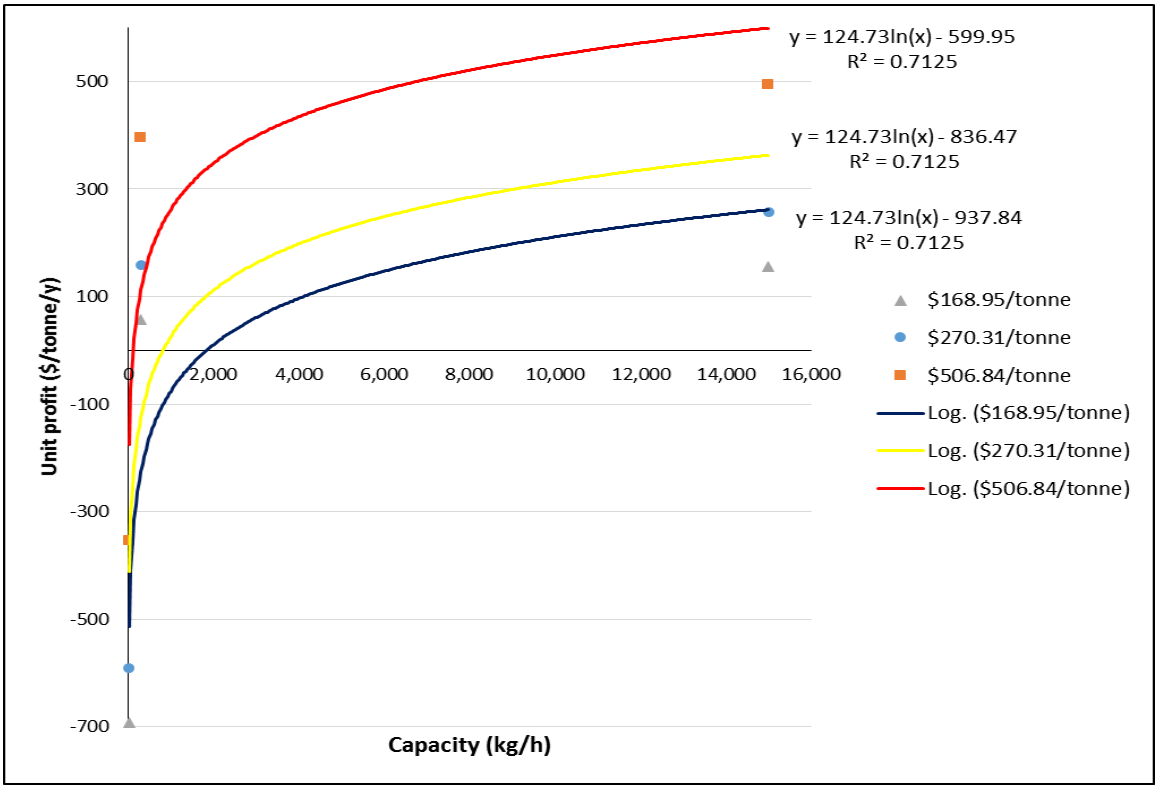

Figure 4.14. Unit profit of DDGS fractionation with various DDGS prices.

CHAPTER 5

LIFE CYCLE ASSESSMENT (LCA) AND TECHNO-ECONOMIC ANALYSIS (TEA) OF TILAPIA-BASIL AQUAPONICS

This chapter is based on a manuscript to be submitted to *Agricultural Engineering International*.

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Abstract

Aquaponics is the system combining hydroponic and aquaculture, in which fish and plants are raised together, and they can be beneficial from each other as well as to each other. When the system is maintained properly and is in a balance status, aquaponics will mimic the natural ecosystem, use much less water than traditional aquaculture, and have almost no effluent. As a result, it is thought more environmentally friendly and sustainable. In this study, both Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) of a tilapia and basil aquaponic system were conducted. Three scales, including a truly running system, pilot scale, and commercial scale of aquaponics were considered and analyzed. This study provided environmental impacts and profitability for operating aquaponics in the Midwest of U.S. It also showed that the operating scale and basil price had obvious effect on profits. When the scale was large enough, such as with the grow bed area of 75.6 m^2 and when the basil price equals to or is great than $60/kg, operating aquaponics was profitable.

Keywords:

Aquaponics, Life cycle assessment (LCA), Techno-economic analysis (TEA), Tilapia, Basil, Greenhouse gas emission, cost, profit

5.1 Introduction

Aquaponics is the system combining hydroponic and aquaculture, in which fish and plants are raised together and be beneficial from as well as to each other. The bacteria in the system convert fish waste into nutrients for plants, and plants absorb nutrients and other toxic components to maintain proper living environment for fish (Love et al, 2014). When the system is maintained properly and in a balance status, aquaponics will mimic the natural ecosystem, use much less water than traditional aquaculture, and have almost no effluent, as a result, it is thought more environmental friendly and sustainable (Blidariu el al, 2011).

Aquaponics is a relatively new biosystem. There were some studies about the mechanism and nutrient cycle in the integration of fish and plants, which were reviewed as in Chapter 1. So far there is no LCA study on aquaponics. According to Love et al.(2014), water, energy and fish feed were the top three physical inputs when operating aquaponics, and 95% aquaponics used electricity as the energy source. However, there is no further information about the use distribution, as well as the amount of electricity and its relationship to biomass yield. There were some studies related to the cost and profit for commercial-scale aquaponics (Bailey et al, 1997; Tokunaga et al, 2013; Bunyaviroch et al., 2013); however, all of them were conducted in tropical area and without the consideration of harsh winter weather like the North America.

In this study, both Life cycle assessment (LCA) and Techno-economic analysis (TEA) of tilapia and basil aquaponics were conducted. Three scales, including a truly running system on Iowa State University campus, pilot scale, and commercial scale of aquaponics were considered and analyzed. This study aimed to provide environmental impacts and profitability for operating aquaponics in the Midwest U.S.A.

5.2 Methodology

An Italian large leaf basil (*Ocimum basilicum*) and Nile tilapia (*Oreochomis niloticus*) aquaponic system was operated on Iowa State University (ISU) campus, which was located in the Forestry Greenhouse, Ames, Iowa. Ames is a city classified with humid continental climate, type Dfa (CDO, 2014). The average amount of annual precipitation is 837 mm (CDO, 2014); and the average low temperature in January is -11.3 ^{o}C, while the average high temperature in July is 29.1 ^{o}C (USCD, 2014). As a result, in order to keep plants and fish alive in the winter, as well as to make profit, ISU aquaponics had to be operated indoor.

There were five main components in our aquaponics: fish culture tank, where the fish stayed from fingerling until harvest; mechanical and biological biofilter, which transferred fish waste to nitrite and nitrate that could be used as fertilizer by plants; plant grow bed, where plants grew from two weeks after being sowed until harvest; sump tank with pump, where water from plant grow bed recirculated back to the fish tank; and air blower, which provided air to both fish and plant roots.

There were three independent systems in our greenhouse, which could be thought as replications during experiments. For each system, the rectangular fish culture tank was of 74-cm long, 50-cm wide, and 65-cm high. Generally there would be 158 L water in the fish tank. Plastic mesh cover was used to prevent the escape of fish, and air stones were set inside the tank to provide enough oxygen. With the aeration provided by air stones, the maximum stock density of tilapia could reach up to 120 kg/m^3 (Rakocy, 1989). Typically it took 6 to 7 month for tilapia to grow from hatchery to 450-680 g size which is ready to

harvest (GAA, 2003). The feed conversion ratio (FCR) for tilapia was between 1.6 and 2.0 (Rakocy, 2004).

The dimension of the filter tank was of 56 cm long, 40 cm wide, and 35 cm high. The water in the filter tank was about 3 cm deep. About 200 of 3.81 cm pronged balls and 0.0283 m^3 PVC ribbon bio fills provide bacteria attached area. Solid filter pad was set above the bio balls and bio fills to pre-filter solid waste and materials. Once the system was set up and in balance, the bio balls and bio fills did not need to be specially treated, while the solid filter pad needed to be cleaned periodically to remove extra materials.

For the hydroponic unit, there are four plant trays in our system, and four age stages of plants were planted separately: the youngest ones needed the least nutrients, and were planted at the far end of the outflow from fish tank; while the oldest ones requiring most nutrients were planted at the near end of the outflow. The area of each tray was about 0.63 m^2, and 16 basils were planted in a tray. Basil was sowed into the holes of starting plug sheets which were made from molten rocks and stayed in the sheets for two weeks. Then basils were transplanted into the rafts floating on the trays which were at the far end of the outflow from fish tank. Basils at the same age were then moved closer toward the near end of the outflow every week. After four weeks' growing in the grow beds, which equaled six weeks after being sowed, basils were ready to harvest.

The analysis was based on the assumption that the system was stable and run at ideal situation, which meant that there was no large-scale of fish or plant disease, and no extra fertilizer was required. Both TEA and LCA were directly conducted with the information from our ISU aquaponics. The ISU aquaponics was used as a baseline and then the results were scaled up to 10 and 300 times of the baseline. Based on the survey

conducted by Love et al. (Love et al., 2014), the water volumes varied from 3 to 600,000 gallon (about 11 to 2,271,247 L), and our 300 times of the baseline system had a water volume of 216,900 L, which was a reasonable commercial-scale. For the baseline, most of the information of building materials and aquaponics equipment was the same with those we used in ISU aquaponics , and only a small part of them were substituted with alternative brands, but still with the same major character. All the facility and equipment information came from retail merchandise website.

5.2.1 System Boundary and Fractionation Flowchart

Since the study was based on the assumption that an existing aquaponics was running ideal, the system boundaries had to adapt to this purpose. In this study we only considered LCA and TEA within the two processes of fish culture and plant growing. The system boundary and flowchart were shown in Figure 5.1, and the system characters were shown in Figure 5.2.

5.2.2 Functional Unit

Both TEA and LCA were analyzed based on a functional unit of 1 kg tilapia and 1 kg basil. Total annual impact, and impact per kg tilapia and impact per kg basil were calculated. Since the price of basil varied and influenced the profit much more than the price of tilapia, the system unit profit was calculated only on the base of 1 kg basil.

5.2.3 Main Assumptions

5.2.3.1 Main assumptions for baseline (grow bed area 7.56 m^2)

In the baseline, one greenhouse with the size of 26.76 m^2 was the facility to set up the aquaponics system. Three 50 gallon (189 L) fish tanks were used for fish culture, and

the total grow bed area was 7.56 m^2. The total water volume in the system was about 723 L.

5.2.3.2 Main assumptions for 10 times of baseline (grow bed area 75.6 m^2)

In the 10 times of baseline, one greenhouse with the size of 140.47 m^2 was the facility to set up the aquaponics system. Three 500 gallon (1890 L) fish tanks were used for fish culture, and the total grow bed area was 75.60 m^2. The total water volume in the system was about 7230 L.

5.2.3.3 Main assumptions for 300 times of baseline (grow bed area 2041.20 m^2)

In the 300 times of baseline, three greenhouses with the size of 802.68 m^2 was the facility to set up the aquaponics system. Thirty 500 gallon (1890 L) fish tanks were used for fish culture, and the total grow bed area was 2041.20 m^2. The total water volume in the system was about 216900 L.

5.2.4 Assumptions for LCA

(1) The environmental impacts we considered contain energy use and greenhouse gas emissions. Based on our aquaponics experience, electricity and natural gas were the two types of energy consumed; water was also a large input. The electricity loss during transportation was negligible. The three greenhouse gas emissions we considered were carbon dioxide, methane, and NO_x.

(2) The electricity came from a coal-fired plant. The greenhouse gas emissions of producing electricity from coal and producing natural gas were shown in Table 5.1 (Spath et al., 1999; Riva et al., 2004).

5.2.5 Assumptions for TEA

(1) Based on our operation, the weekly water loss was 10%.

(2) The effective volume of each fish tank was 84%, and the maximum fish biomass was 120 kg/m^3.

(3) The surviving rate of fish from fingerlings to harvest was 90%, and the harvest cycle was 6 month.

(4) There were 16 basils in one tray and there were 12 trays in total for the baseline. 25% basils would be ready for harvest each week.

(5) Both fish and basil yield in the two larger scales were 10 times and 300 times of the baseline, respectively.

(6) The average wet weight of basil was 27.3 g/plant, and the basil price was considered at $10, $15, $20, $40, $60, $80, and $100/kg.

(7) The average weight of tilapia was 0.68 kg (1.5 lb) per fish, and fresh tilapia price was $ 9.00/kg (FishChoice, 2014).

(8) The fish feed conversion ratewas 1.6.

(9) According to Ames municipal utilities, the winter for water and electricity started from Nov.1 and lasted till Jun 30, and the summer started from Jul 1 and lasted till Oct 30.The average electricity price was $0.10/ kWh; and the average water price was $0.02/$ft^3$.

(10) The operating time of fans, water pump, air pump, UV clarifier was 24 h/d, and 365 d/y.

(11) In the winter, in order to provide supplemental light, the operating time of timer for light supplementation was 24 h/d, and 22 weeks, and the operating time of light was 4 h/d, and 22 weeks. No light supplementation was needed in summer.

(12) The operating time of heater was 24 h/d, and 198 d/y.

(13) The required labor was 52 week/y for all three scales, and 10 h/week, 20 h/week, and 120 h/week for the baseline, 10 times of baseline, and 300 times of baseline, respectively.

(14) The hourly labor payment was $12/h.

(15) The yearly interest rate was 5.5%, insurance rate was 0.462% and tax rate was 0.35%.

(16) The yearly maintenance cost was 1% of total capital cost.

(17) Since the greenhouse was free shipping, the freight was 1% of the costs of all other initial equipment.

(18) Both the types and numbers of the equipment varied according to different scale sizes.

(19) For the 10 times of baseline and 300 times of baseline, the proportions of wood were less because 500 gallon tanks were supposed to set on the ground.

(20) Due to large amount of purchase, most prices of the items in the 10 times of baseline were 90% of that in Baseline; and 80% for the 300 times of baseline.

(21) No extra fertilizer was used.

(22) The depreciation and salvage value at the end of service life were assumed to be 0.

5.3 Results and Discussion

The LCA results showed that all of the annual total environmental impact categories increased as the scale expanded. The details were shown in Tables 5.2 and 5.4, and Figures 5.3-5.5 and 5.9-5.11. For annual water use, which was shown in Figure 5.3, the regression

line was linear trend between water use and grow bed area. It was because of specific maximum fish biomass production in unit water volume. And this also was the reason that unit water use remained the same, which was shown in Figure 5.6. In Figure 5.4, 5.5, and 5.9-5.11, the annual environmental impacts and grow bed area could be regressed as both linear and exponential trend lines, and both those two type regressions had reasonable R^2. In real aquaponics operation, the shaded region referred to the flexibility caused by different operation efficiency, such as the variance of fish feed nutrient, variance of plant growing time, variance of equipment performance, etc. The unit environmental impact categories decreased as the scale expanded, which were shown in Table 5.3 and 5.5. The regression lines were shown power or logarithmic relationship between unit environmental impact categories and grow bed area, which were shown in Figures 5.7, 5.8, and 5.12-5.14.

For each scale, the annualized cost was considered including capital cost and operating cost, which were shown in Tables 5.6-5.11. As shown in Figure 5.15, the annualized total cost increased as the scale expanded, and the relationship of annualized total cost and grow bed area could be regressed as both linear and exponential, and both those two type regressions had reasonable R^2. Similar to LCA, the shaded region referred to the flexibility caused by different operation efficiency. The annualized unit cost was considered on the base of per kg tilapia and per kg basil, and the trend lines could be regressed as a power relationship between unit cost and grow bed area. The details of annualized total cost and unit cost for three scales were shown in Table 5.12 and Figures 5.15 and 5.16.

Since the price of basil varied a lot in different markets, both the annual total profit and system unit profit were influenced strongly by the price of basil. The basil price we

considered were a$10/kg, $15/kg, $20/kg, $40/kg, $60/kg, $80/kg, and $100/kg. When basil price was lower or equaled to $20/kg, none of the three scales could make positive profit; when basil price was $40/kg, only the 300 times of baseline could make positive profit; and when basil price was greater or equaled to $60/kg, both 10 times of baseline and 300 times of baseline could make positive profit. The details of the total annual profit and unit profit for three scales were shown in Tables 5.13 and 5.14 and Figures 5.17 and 5.18.

There were some studies focusing on the cost and profit for commercial-scale aquaponics (Bailey et al, 1997; Tokunaga et al, 2013; Bunyaviroch et al., 2013), but these studies were conducted in a tropical area and without the consideration of winter with low temperature like the Midwest U.S.A. Bunyaviroch et al. investigated a commercial aquaponics in Puerto Rico and concluded that aquaponics was viable there but the profitability was limited. Based on a techno-economic study of aquaponics in South Africa, Lapere indicated that high capital and operating cost made it difficult to make profit (Lapere, 2010). The present work filled the data gap for aquaponics operating on U.S. mainland, and both supplement light and heating were included in our calculations. Compared to the tropical area, it was harder for small aquaponics operated in Midwest U.S.A. to make profit; and even for those commercial scales, the basil price was the most important indicator to predict whether aquaponics was profitable. Our work was also consistent with the investigation conducted by Love et al., which showed that only 31% of operators made profits during the year between 2012 and 2013 (Love et al., 2015).

Based on our TEA, how to sell basil for a relatively high price was the key issue to profitability. It was an ideal option to sell basil via farmers market, or sell them to local

restaurant, other than sell basil via wholesale. In general, the basil price sold via farmers market and local restaurant was much higher than via wholesale.

While our work focused on a tilapia-basil aquaponic system, more work needs to be done to explore aquaponics with other fish and plants. Besides, our model was based on the assumption that fish are raised in plastic tanks and plants grow using rafts. More work needs to be done to explore aquaponics using other system components.

For better understanding the Iowa State University aquaponics, more pictures could be found in Figures 5.19- 5.24.

5.4 Conclusions

Compared with previous work, the present study was the first LCA and TEA model for aquaponics operated in mainland in U.S.A., where the winter is cold and both supplement light and heating are required to maintain all year round operation.

Based on our LCA and TEA analyses, both unit environmental impacts and unit cost of tilapia-basil aquaponic system decreased as the operation scale expanded. This study provided useful information for basil and tilapia aquaponics at different scales. The results indicated that when the scale was large enough, such as with the grow bed area of 75.6 m^2, aquaponic prediction was profitable when the basil price equaled to or was great than \$60/kg. More work is required to conduct LCA and TEA for other types of aquaponics in the future.

5.5 Acknowledgement

The author would like to thank Mr. David Pattillo for providing aquaponics information for LCA and TEA calculations.

5.6 References

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Table 5.1. Air emission of producing electricity from coal and producing natural gas.

Emission category	Electricity g/kWh	Natural gas g/m^3
CO_2	1,022[a]	1,248.000[b]
CH_4	0.91[a]	247.600[b]
NO_x	3.35[a]	5.158[b]

a: Spath, P. L., and Mann, M. K. (1999). Environmental Aspects of Producing Electricity from a Coal-Fired Power Generation System-A Life Cycle Assessment. National Renewable Energy Laboratory, USA.

b: Riva, A., D'Angelosante, S., and Trebeschi, C. (2006). Natural gas and the environmental results of life cycle assessment. Energy, 31(1), 138-148.

Table 5.2. Annual water and energy use of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed area (m^2)	Annual water use (m^3/y)	Annual electricity use (kWh/y)	Annual natural gas use (m^3)
7.56	3.74	11,052.93	7,403.97
75.6	37.40	23,836.98	43,077.62
2041.2	1,121.87	641,830.89	387,698.58

Table 5.3. Unit water and energy use of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed area (m^2)	Unit water use		Unit electricity use		Unit natural gas use	
	m^3/ kg basil/y	m^3/ kg tilapia/y	kWh / kg basil/y	kWh / kg tilapia/y	m^3/ kg basil/y	m^3/ kg tilapia/y
7.56	0.05	0.03	162.10	96.57	108.58	64.69
75.6	0.05	0.03	34.96	20.83	63.18	37.64
2041.2	0.05	0.03	31.38	18.69	18.95	11.29

Table 5.4. Annual greenhouse gas emission of tilapia-basil aquaponic systems with various grow bed areas.

Grow beds area (m^2)	Annual CO_2 emission (g/y)	Annual CH_4 emission (g/y)	Annual NO_x emission (g/y)
7.56	20,536,243.01	1,843,280.15	75,216.97
75.6	78,122,261.77	10,687,710.46	302,048.24
2041.2	1,139,799,004.33	96,578,235.40	4,149,882.78

Table 5.5. Unit greenhouse gas emission of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed area (m^2)	Unit CO_2 emission		Unit CH_4 emission		Unit NO_x emission	
	g/ kg basil/y	g/ kg tilapia/y	g/ kg basil/y	g/ kg tilapia/y	g/ kg basil/y	g/ kg tilapia/y
7.56	301,172.69	179,421.02	27,032.48	16,104.37	1,103.09	657.16
75.6	114,569.60	68,253.85	15,673.98	9,337.64	442.97	263.89
2041.2	55,718.78	33,193.98	4,721.20	2,812.62	202.87	120.86

Table 5.6. Capital cost of tilapia-basil aquaponics with grow bed area 7.56 m^2.

Component	Type	Price ($/each)	Quantity	Total Cost ($)
Greenhouse	16’ x 18’	11,250.00	1	11,250.00
Fan	ValuTek™ 12" - 3 Speed	215.00	2	430.00
Heater	Modine™ Effinity 55K BTU Nat Gas	1,399.00	1	1,399.00
Lumber				614.44
Hardware				530.96
PVC				591.44
Water pump	Simer Portable 2305	50.37	3	151.11
Blower	Aquatic Eco-systems SL22	272.65	3	817.95
UV clarifier	TetraPond 9W UVC 9	103.11	3	309.33
Light	400W Fixture w/HPS Lamp - 120V	209.95	8	1,679.60
Tanks				1,416.22
Rubber liner	Smartpond 1,100-Gallon Rubber	159.00	1	159.00
pH/ ORP meter	HQ11d Portable pH/ORP Meter	514.00	1	514.00
Others				1,085.67
Equipment initial costs ($)				**20,948.72**
Electrical wiring and controls				837.95
equipment installation				1,920.00
equipment freight				96.99
Total equipment initial costs ($)				**23,803.66**
Engineering and design				1,666.26
Total capital costs ($)				**25,469.92**
Capital costs per year ($)				**3,379.04**

Table 5.7. Operating cost of tilapia-basil aquaponics with grow bed area 7.56 m^2.

Component	Total cost ($/y)
Fixed costs	
Interest	1,400.85
Insurance	117.67
Tax	89.14
Subtotal ($/year)	**1,607.66**
Variable costs	
Yearly use materials	1,399.36
Chemicals	26.47
Basil seeds	9.60
Fish feed	996.20
Fish fingerlings	278.63
Water	3.01
Electricity	1,121.50
Natural gas	718.74
Labor	6,240.00
Maintenance and repair	254.70
Subtotal ($/year)	**11,048.21**
Total fixed costs ($/year)	**12,655.88**

Table 5.8. Capital cost of tilapia-basil aquaponics with grow bed area 75.6 m^2.

Component	Type	Price ($/each)	Quantity	Total cost ($)
Greenhouse	21'x72'	15,674.00	1	15,674.00
Fan	ValuTek™ 12" - 3 Speed	215.00	2	430.00
Heater	Modine™ Power 320 K BTU Nat Gas	1,899.00	1	1,899.00
Lumber				2,006.82
Hardware				2,841.46
PVC				2,111.15
Water pump	Simer ½ HP	159.99	3	479.97
Blower	Aquatic Eco-systems SL22	272.65	3	817.95
UV clarifier	TetraPond 9W UVC 9	103.11	3	309.33
Light	400W Fixture w/HPS Lamp - 120V	188.96	40	7,558.20
Tanks				4,802.23
Rubber liner	Smartpond 1,100-Gallon Rubber	143.10	6	858.60
pH/ ORP meter	HQ11d Portable pH/ORP Meter	514.00	1	514.00
Others				1,508.45
Equipment initial costs ($)				**47,811.15**
Electrical wiring and controls				1,672.45
equipment installation				3,600.00
equipment freight				261.37
Total equipment initial costs ($)				**47,344.97**
Engineering and design				3,314.15
Total capital costs ($)				**50,659.12**
Capital costs per year ($)				**6,720.83**

Table 5.9. Operating cost of tilapia-basil aquaponics with grow bed area 75.6 m^2.

Component	Total cost ($/y)
Fixed costs	
Interest	2,786.25
Insurance	234.05
Tax	177.31
Subtotal ($/year)	**3,197.60**
Variable costs	
Yearly use materials	4,582.99
Chemicals	122.86
Basil seeds	56.20
Fish feed	8,965.80
Fish fingerlings	2,507.67
Water	30.12
Electricity	2,418.66
Natural gas	4,181.76
Labor	12,480.00
Maintenance and repair	506.59
Subtotal ($/year)	**35,852.65**
Total fixed costs ($/year)	**39,050.25**

Table 5.10. Capital cost of tilapia-basil aquaponics with grow bed area 2041.2 m^2.

Component	Type	Price ($/each)	Quantity	Total cost ($)
Greenhouse	90'x 96'	59,466.60	3	178,399.80
Fan	ValuTek™ 12" - 3 Speed	172.00	9	1,548.00
Heater	Modine™ Power 320 K BTU Nat Gas	1,519.20	9	13,672.80
Lumber				53,515.20
Hardware				75,647.04
PVC				56,041.20
Water pump	Simer ½ HP	127.99	90	11,519.28
Blower	Aquatic Eco-systems SL22	218.12	90	19,630.80
UV clarifier	TetraPond 9W UVC 9	82.49	90	7,423.92
Light	400W Fixture w/HPS Lamp - 120V	167.96	1200	201,552.00
Tanks				109,136.40
Rubber liner	Smartpond 1,100-Gallon Rubber	127.20	180	22,896.00
pH/ ORP meter	HQ11d Portable pH/ORP Meter	514.00	3	1,542.00
Others				33,567.15
Equipment initial costs ($)				**786,091.59**
Electrical wiring and controls				31,443.66
equipment installation				54,000.00
equipment freight				6,076.92
Total equipment initial costs ($)				**877,612.17**
Engineering and design				61,432.85
Total capital costs ($)				**939,045.02**
Capital costs per year ($)				**124,581.01**

Table 5.11. Operating cost of tilapia-basil aquaponics with grow bed area 2041.2 m^2.

Component	Total cost ($/y)
Fixed costs	
Interest	51,647.48
Insurance	4,338.39
Tax	3,286.66
Subtotal ($/year)	**59,272.52**
Variable costs	
Yearly use materials	87,482.64
Chemicals	1,460.34
Basil seeds	368.64
Fish feed	239,088.00
Fish fingerlings	66,841.40
Water	903.53
Electricity	55,047.70
Natural gas	37,635.84
Labor	74,880.00
Maintenance and repair	9,390.45
Subtotal ($/year)	**573,098.54**
Total fixed costs ($/year)	**632,371.06**

Table 5.12. Annualized total cost and system unit cost of tilapia-basil aquaponic systems with various grow bed areas.

Grow bed Area (m^2)	Annualized Total Cost ($/y)	Biomass Quantity (kg)		Annualized Unit Cost	
		Tilapia	Basil	$/kg tilapia /y	$/kg basil /y
7.56	$16,034.91	114.46	68.19	140.09	235.16
75.6	$45,771.08	1,144.58	681.88	39.99	67.13
2041.2	$756,952.07	34,337.52	20,456.28	22.04	37.00

Table 5.13. Annual total profit with various basil prices and tilapia price at $9/kg.

Grow Bed Area (m^2)	Annual Total Profit with Various Basil Price ($/y)						
	$10/kg	$15/kg	$20/kg	$40/kg	$60/kg	$80/kg	$100/kg
7.56	-$14,322.91	-$13,981.97	-$13,641.04	-$12,277.28	-$10,913.53	-$9,549.78	-$8,186.03
75.6	-$28,651.07	-$25,241.69	-$21,832.31	-$8,194.79	$5,442.73	$19,080.25	$32,717.77
2041.2	$243,351.59	-$141,070.19	-$38,788.79	$370,336.81	$779,462.41	$1,188,588.01	$1,597,713.61

Table 5.14. System unit profit of tilapia-basil aquaponic systems with various grow bed areas.

Grow Bed Area (m^2)	System Unit Profit with Various Basil Price ($/y)						
	$10/kg	$15/kg	$20/kg	$40/kg	$60/kg	$80/kg	$100/kg
7.56	-$210.05	-$205.05	-$200.05	-$180.05	-$160.05	-$140.05	-$120.05
75.6	-$42.02	-$37.02	-$32.02	-$12.02	$7.98	$27.98	$47.98
2041.2	-$11.90	-$6.90	-$1.90	$18.10	$38.10	$58.10	$78.10

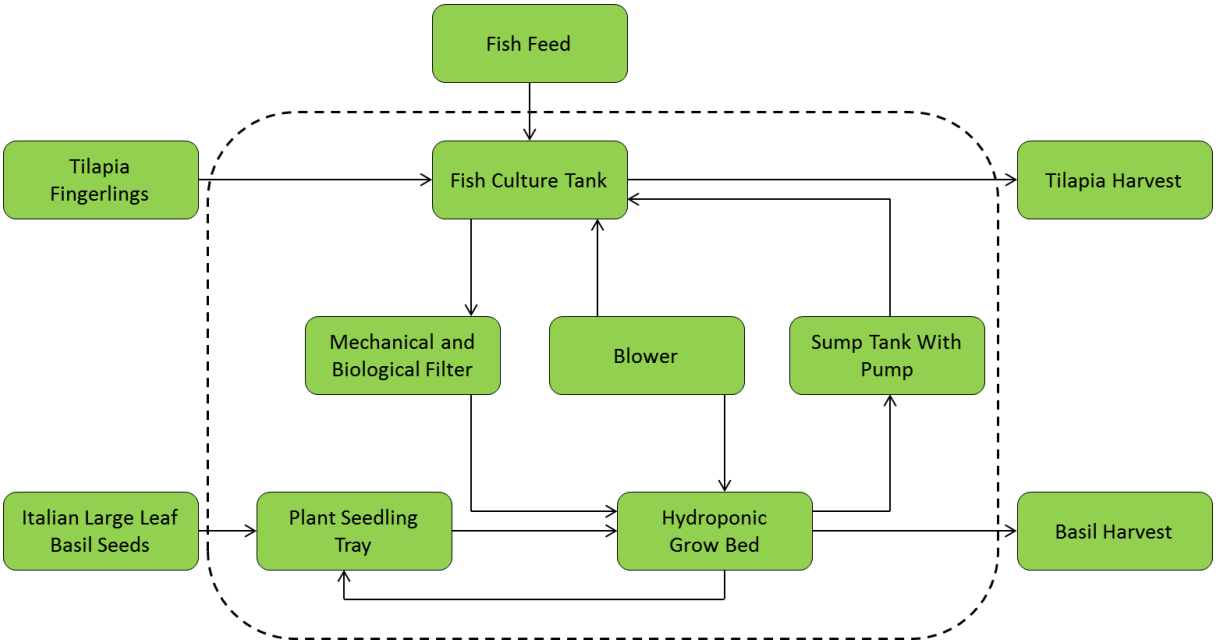

Figure 5.1. Aquaponics system boundary and flowchart.

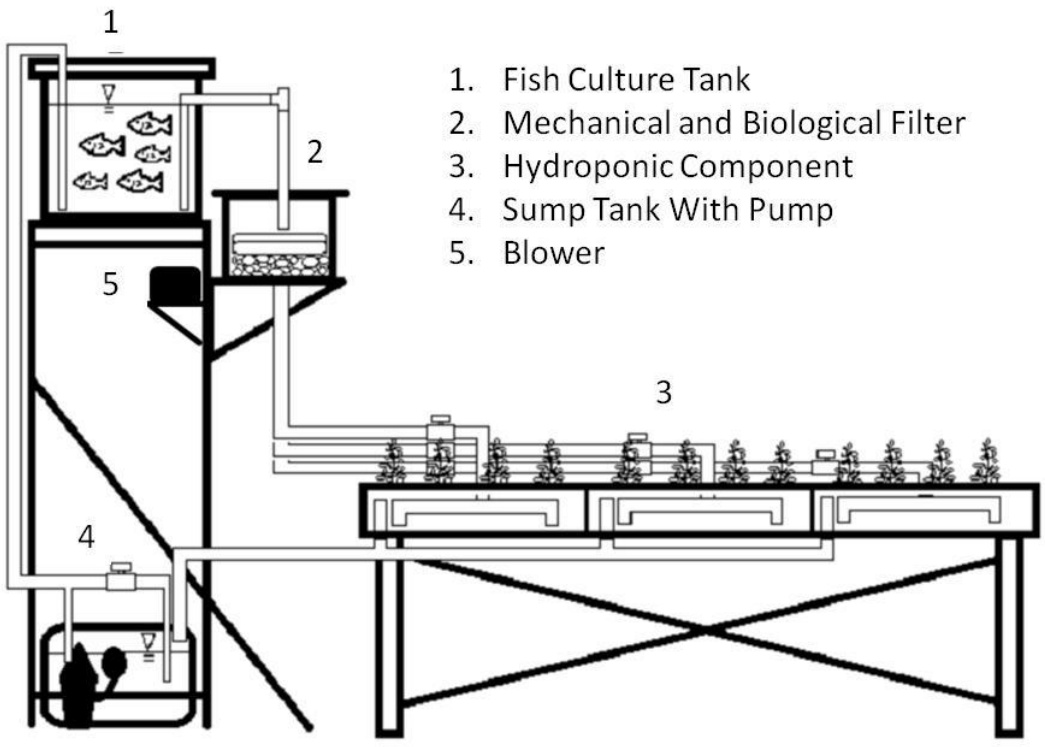

Figure 5.2. Iowa State University Aquaponics character (courtesy of Allen Pattillo).

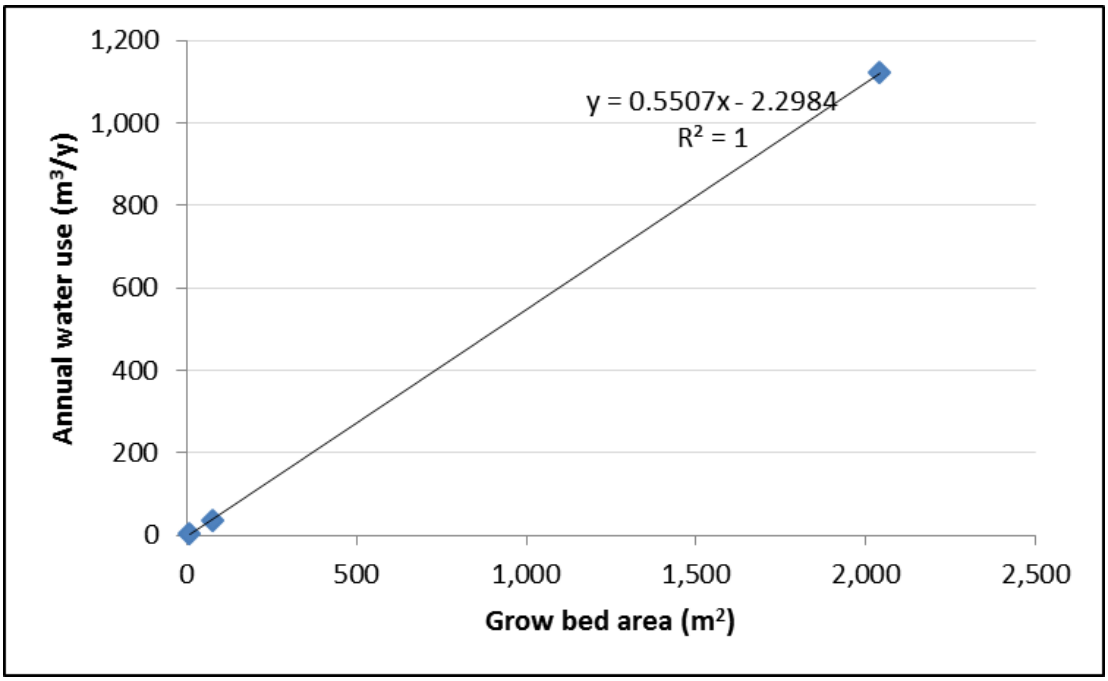

Figure 5.3. Annual water use of tilapia-basil aquaponic systems with various grow bed areas.

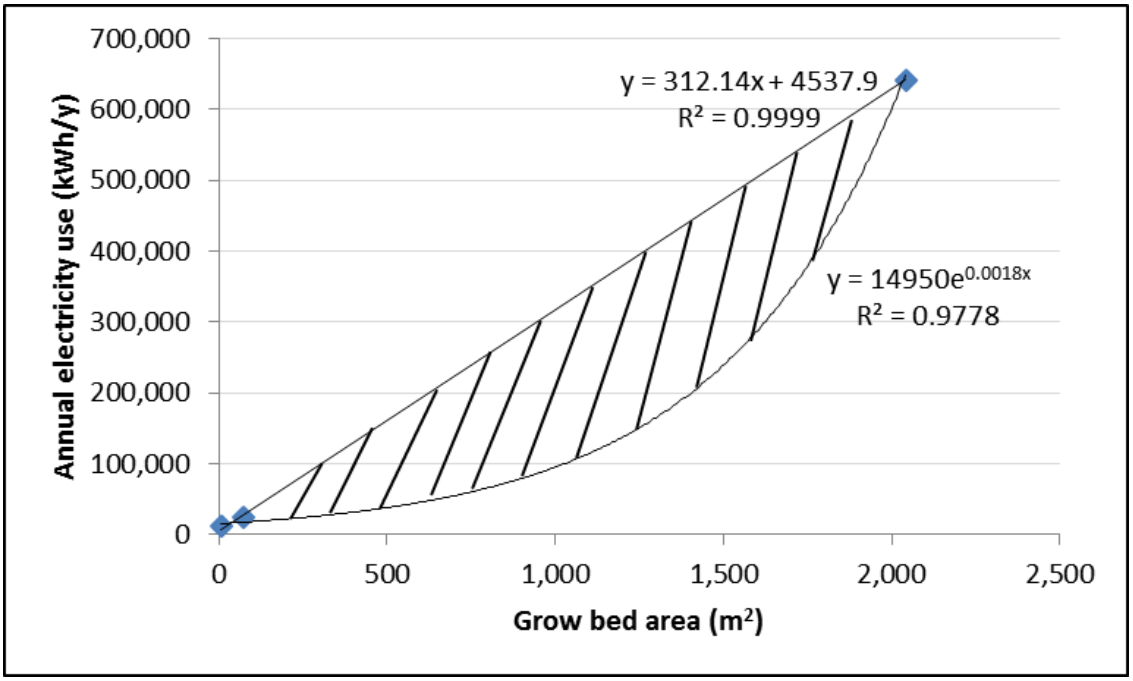

Figure 5.4. Annual electricity use of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

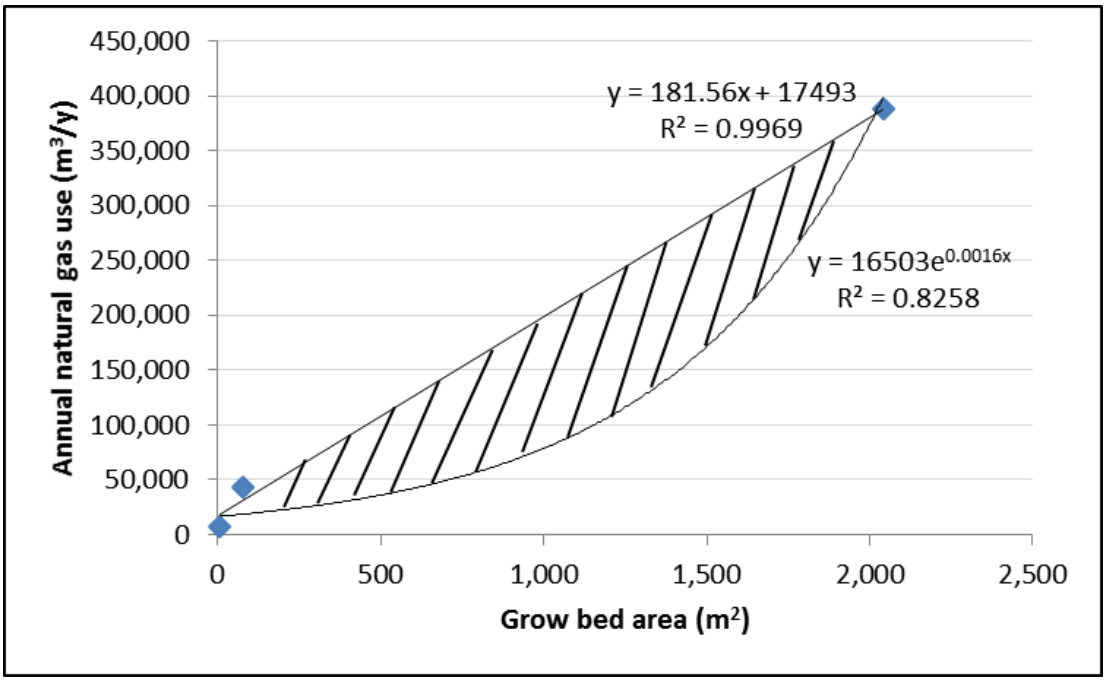

Figure 5.5. Annual natural gas use of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

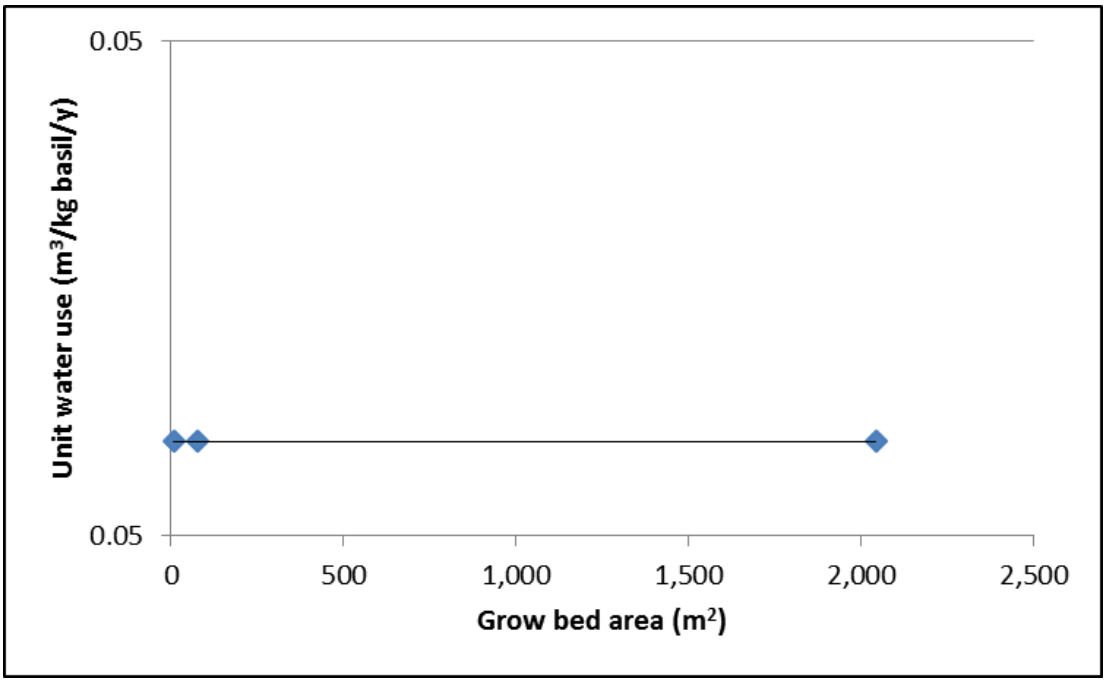

Figure 5.6. Unit water use of tilapia-basil aquaponic systems with various grow bed areas.

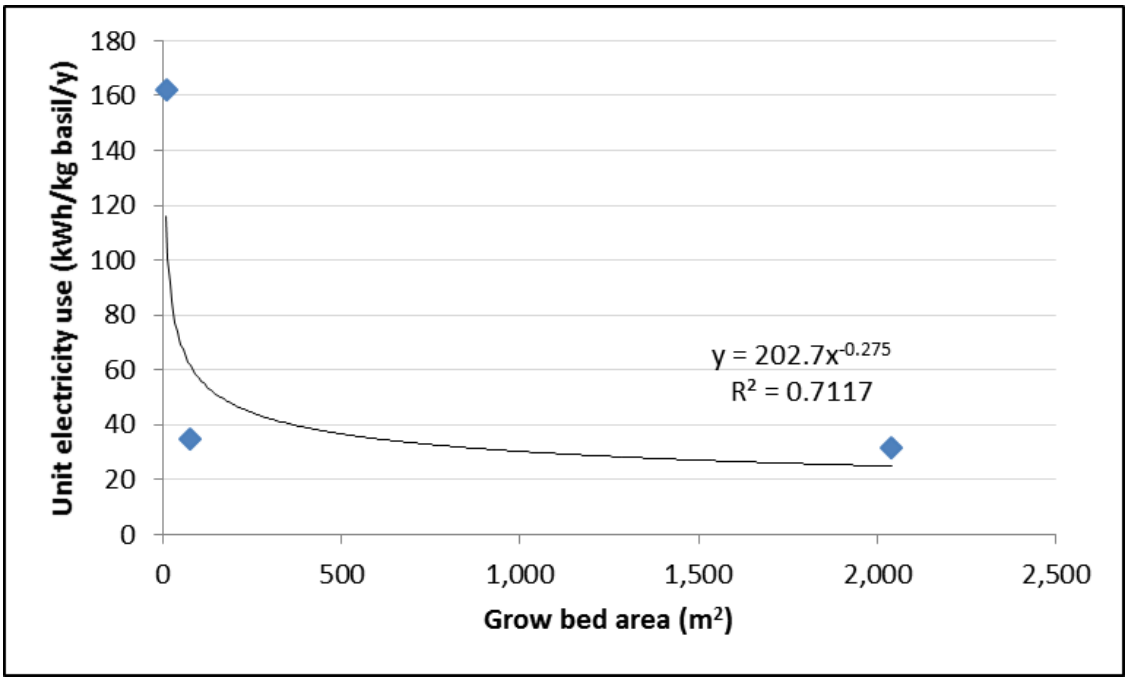

Figure 5.7. Unit electricity use of tilapia-basil aquaponic systems with various grow bed areas.

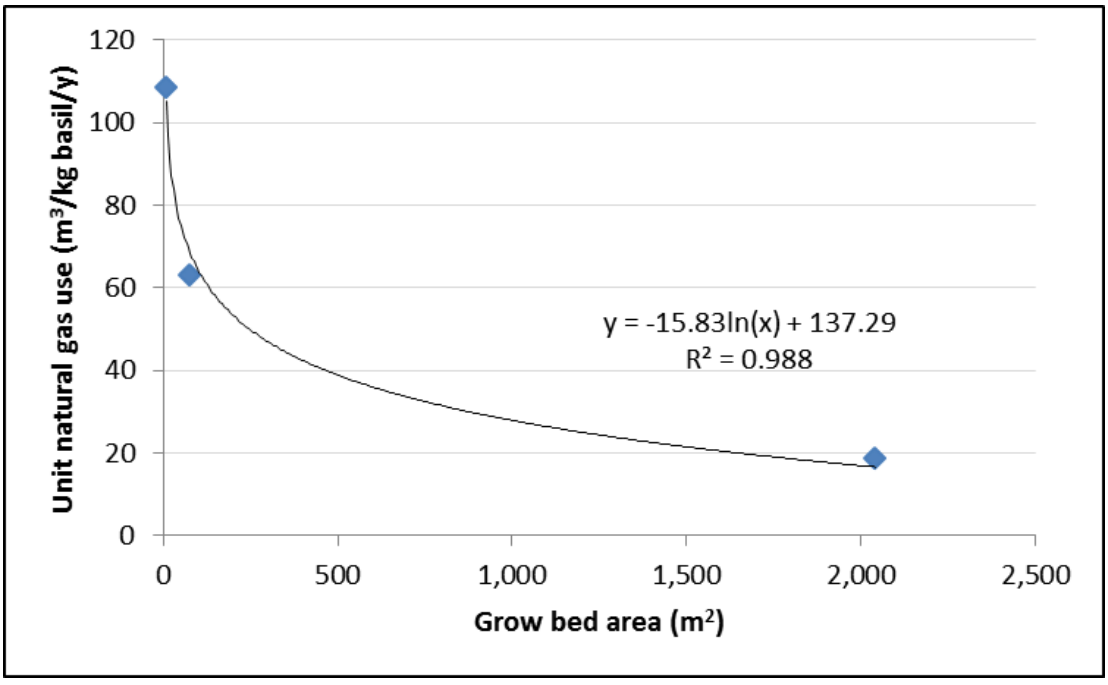

Figure 5.8. Unit natural gas use of tilapia-basil aquaponic systems with various grow bed areas.

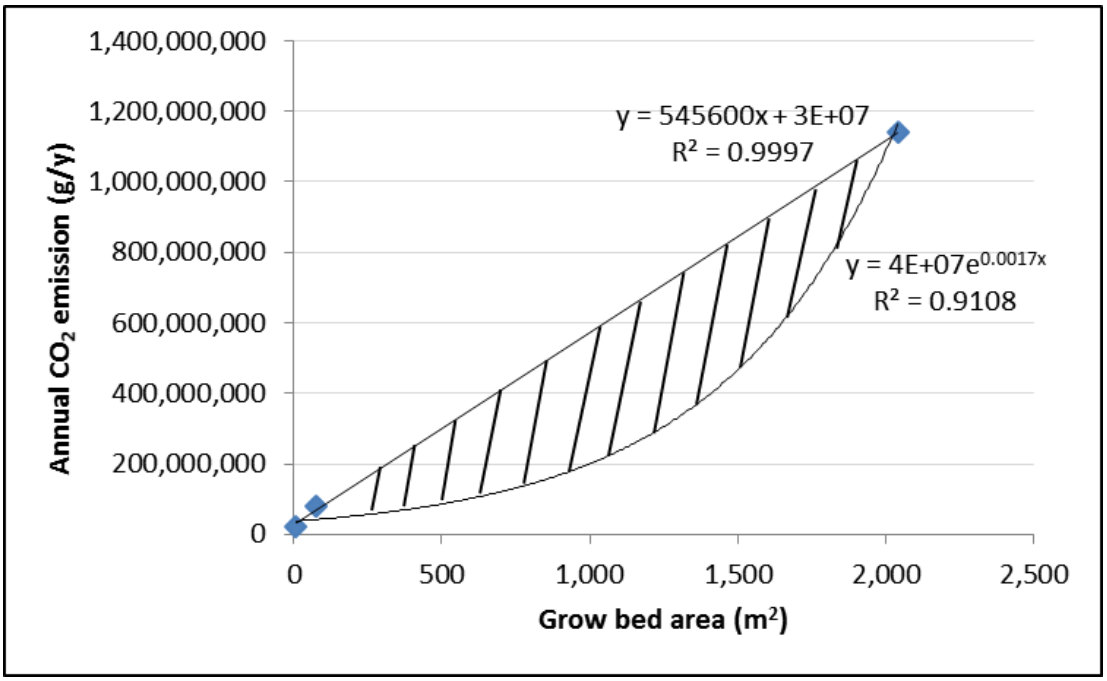

Figure 5.9. Annual CO_2 emission of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

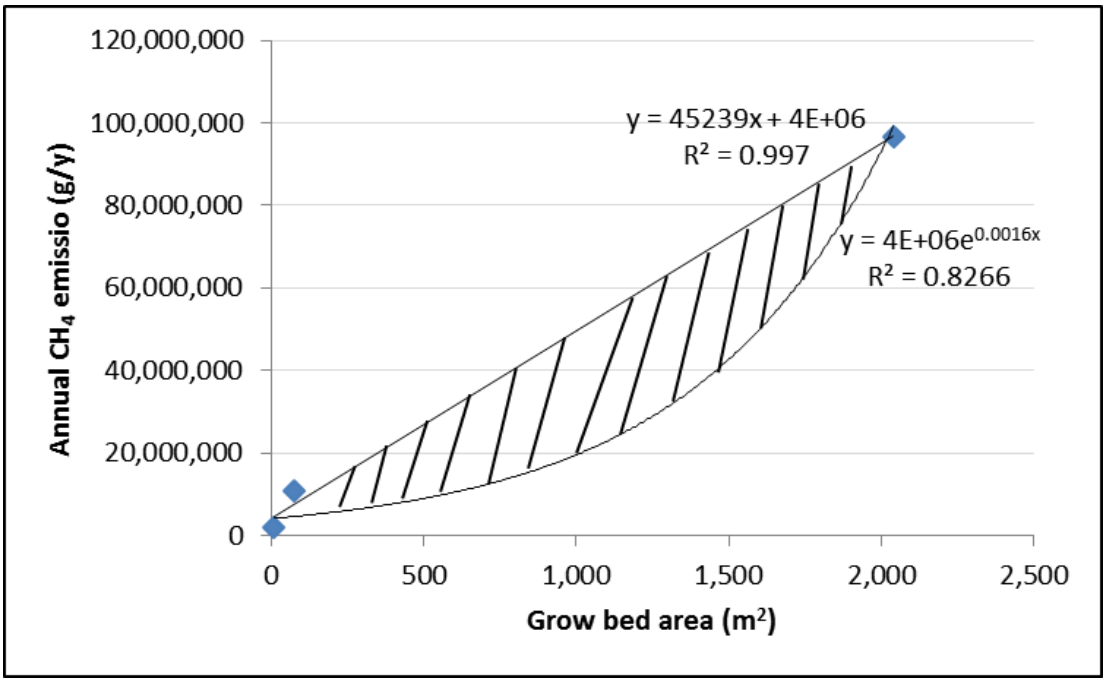

Figure 5.10. Annual CH_4 emission of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

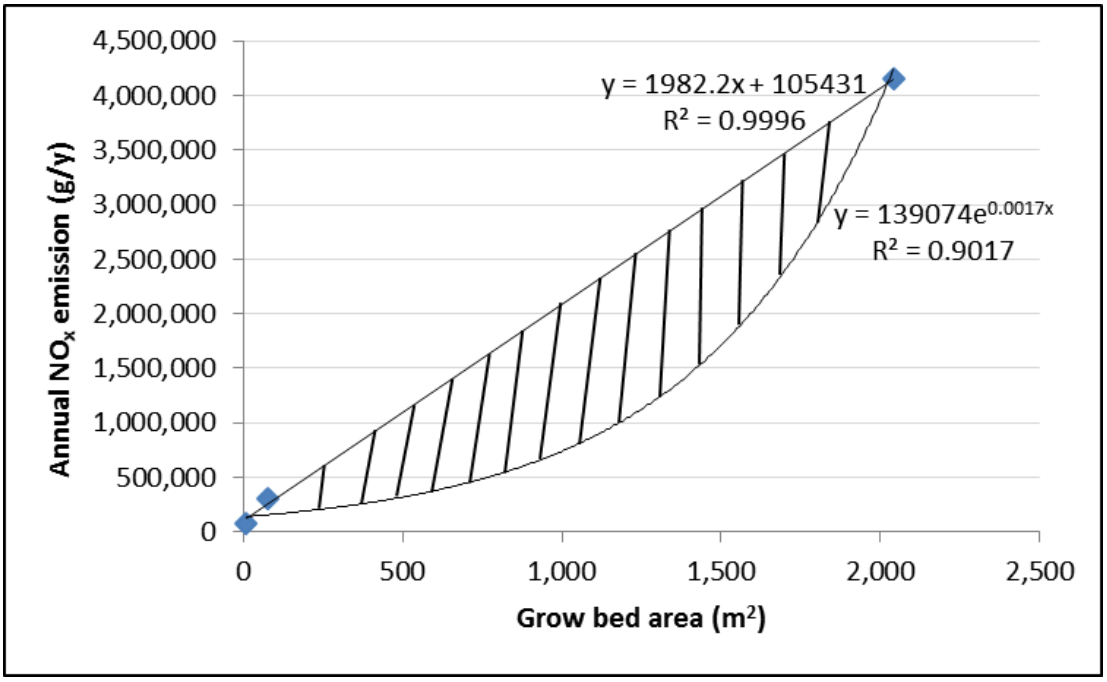

Figure 5.11. Annual NO_x emission of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

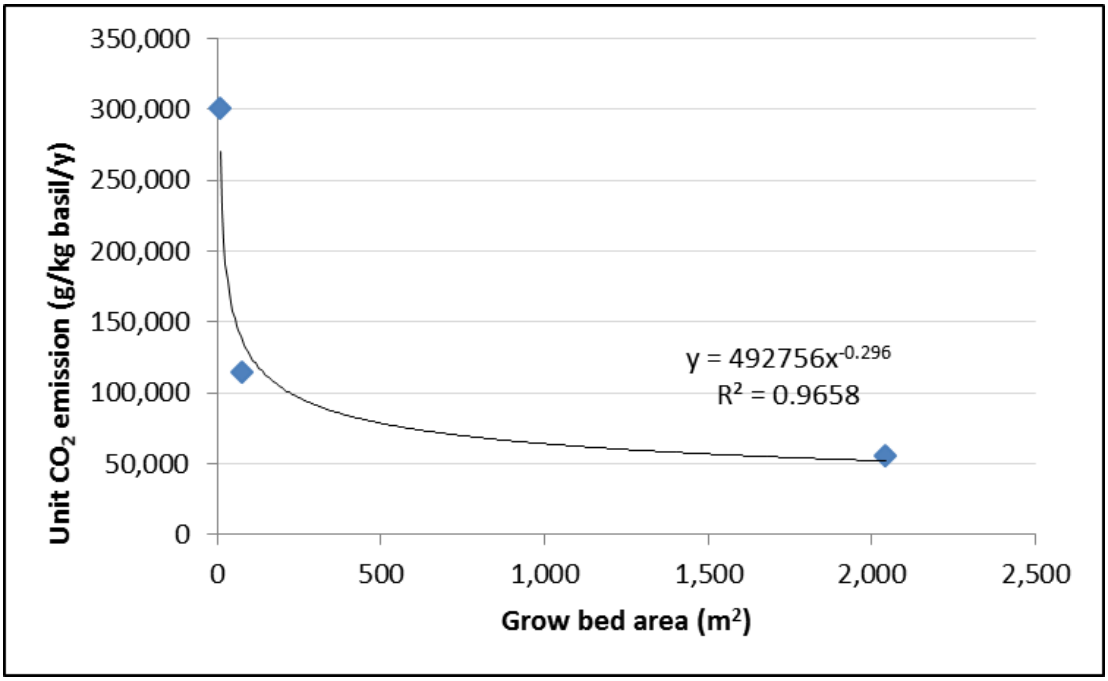

Figure 5.12. Unit CO_2 emission of tilapia-basil aquaponic systems with various grow bed areas.

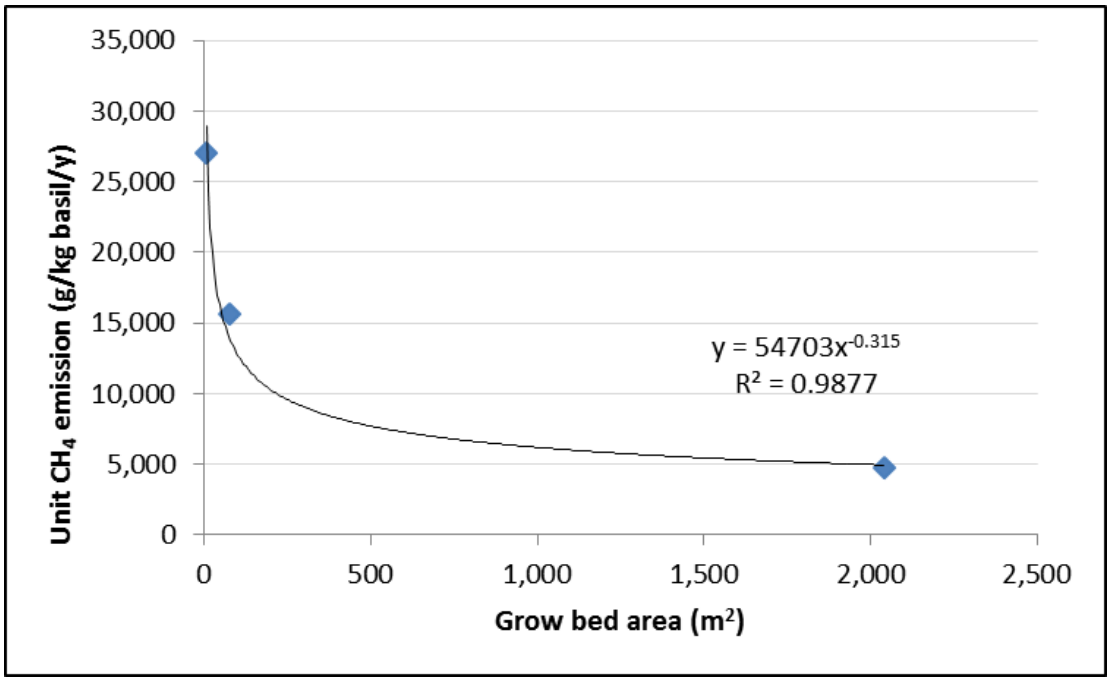

Figure 5.13. Unit CH_4 emission of tilapia-basil aquaponic systems with various grow bed areas.

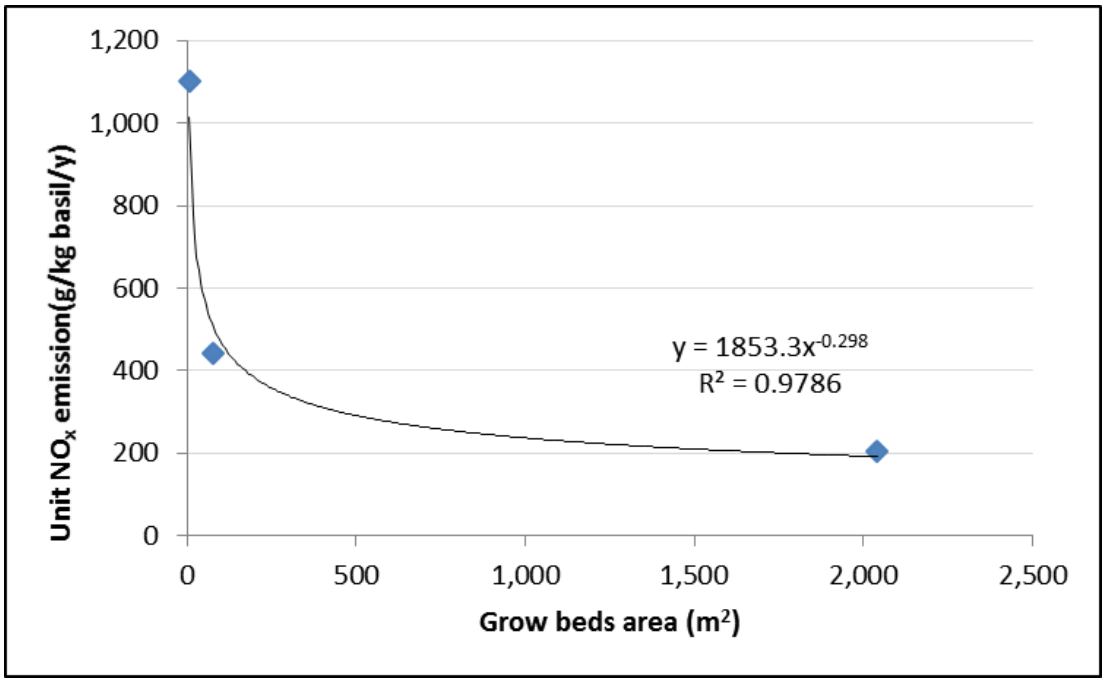

Figure 5.14. Unit NO_x emission of tilapia-basil aquaponic systems with various grow bed areas.

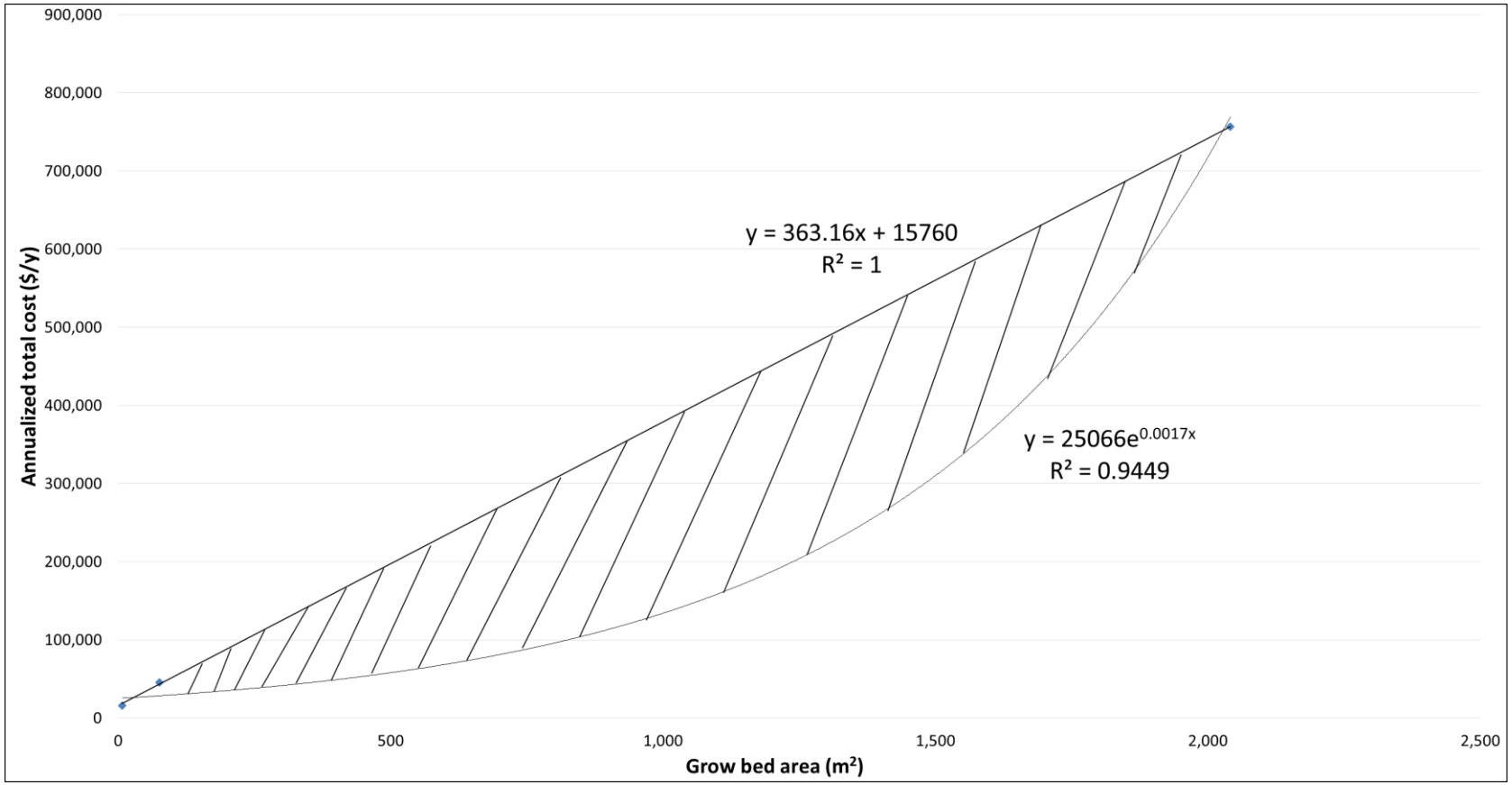

Figure 5.15. Annualized total cost (fish and plants) of tilapia-basil aquaponic systems with various grow bed areas (shaded region refers to the flexibility caused by different operation efficiency).

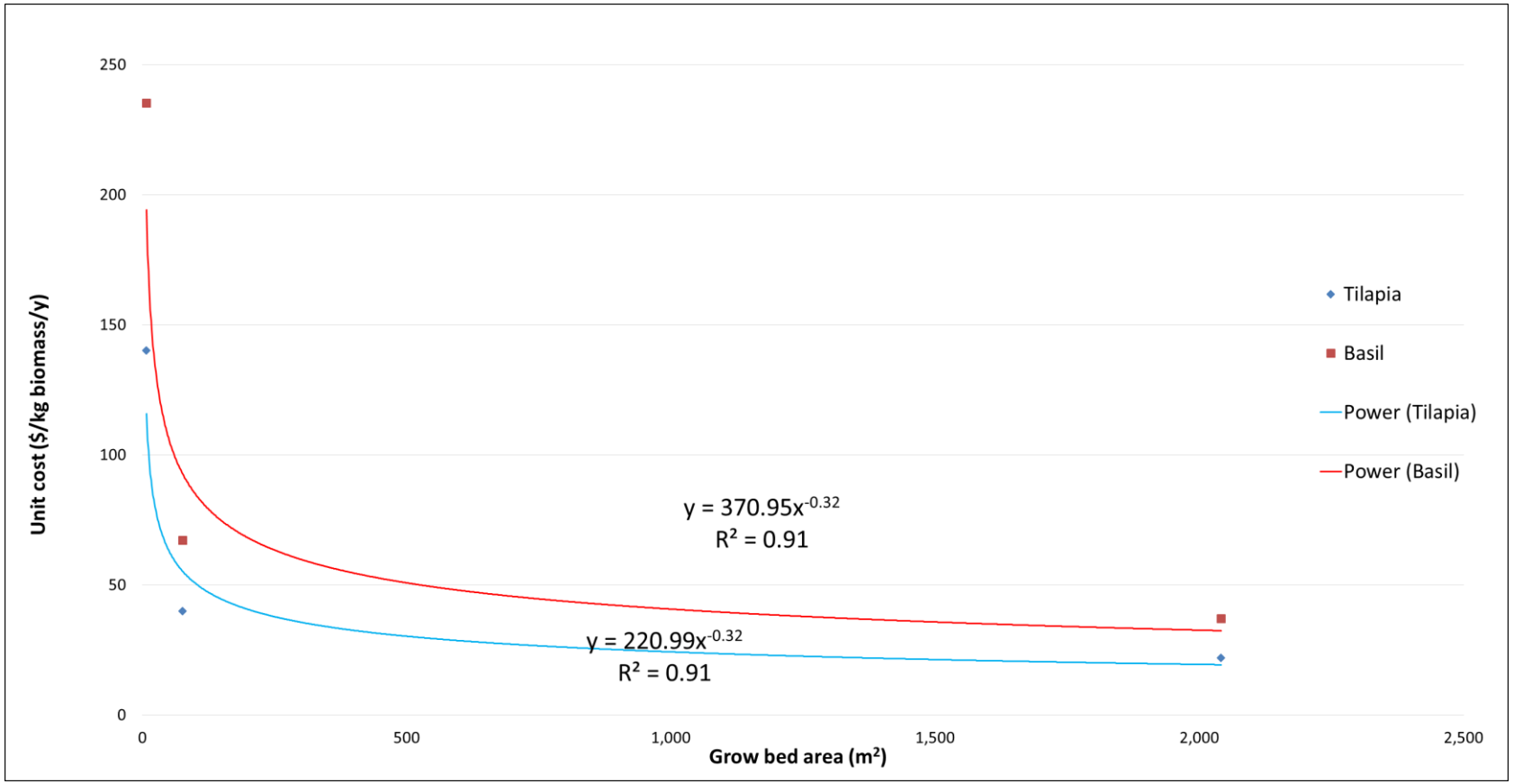

Figure 5.16. System unit cost of tilapia-basil aquaponic systems with various grow bed areas (total cost per unit of biomass produced).

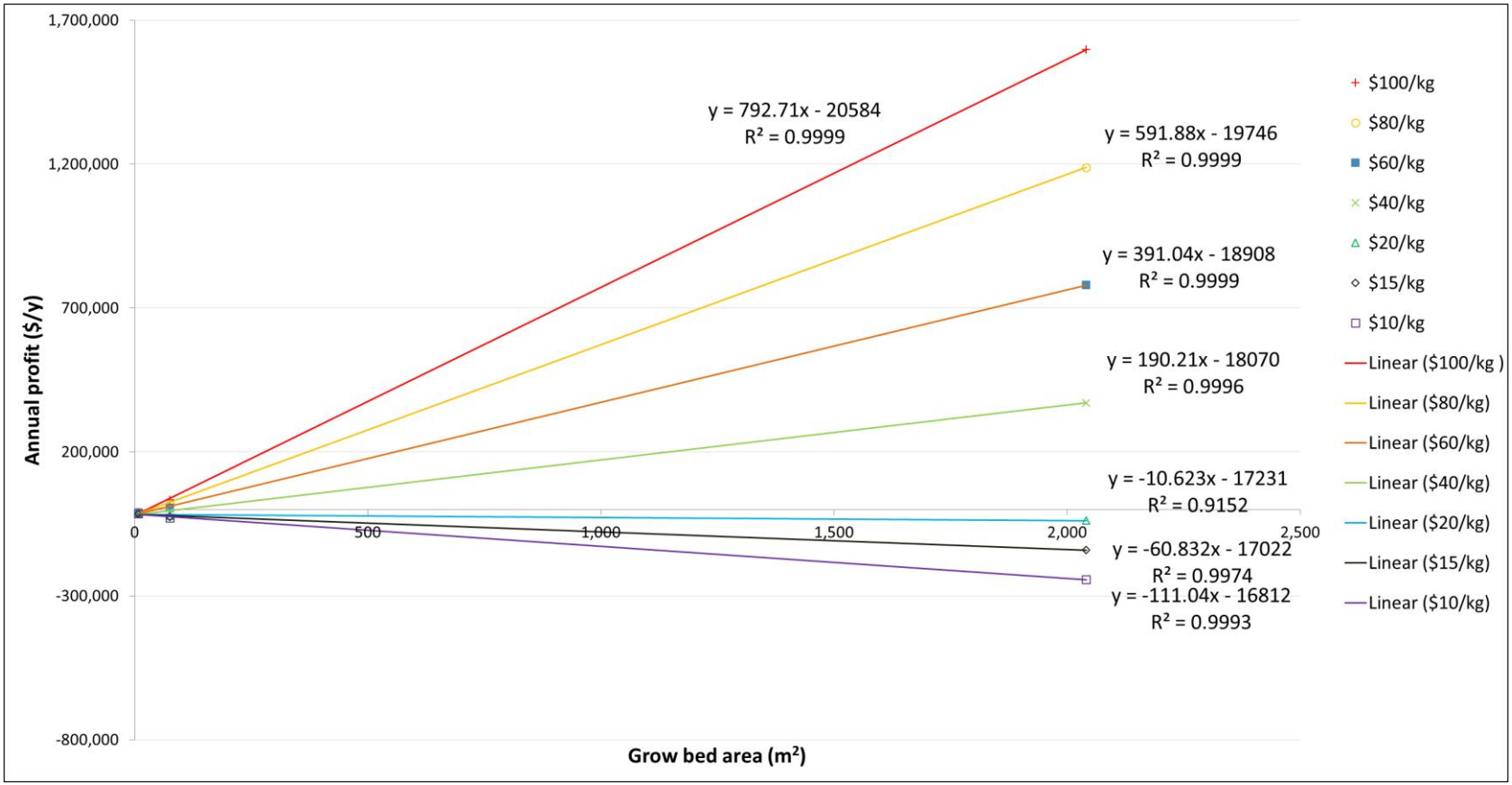

Figure 5.17. Annual total profits with various basil prices of tilapia-basil aquaponic systems with various grow bed areas (for a given tilapia sales price: $9 /kg).

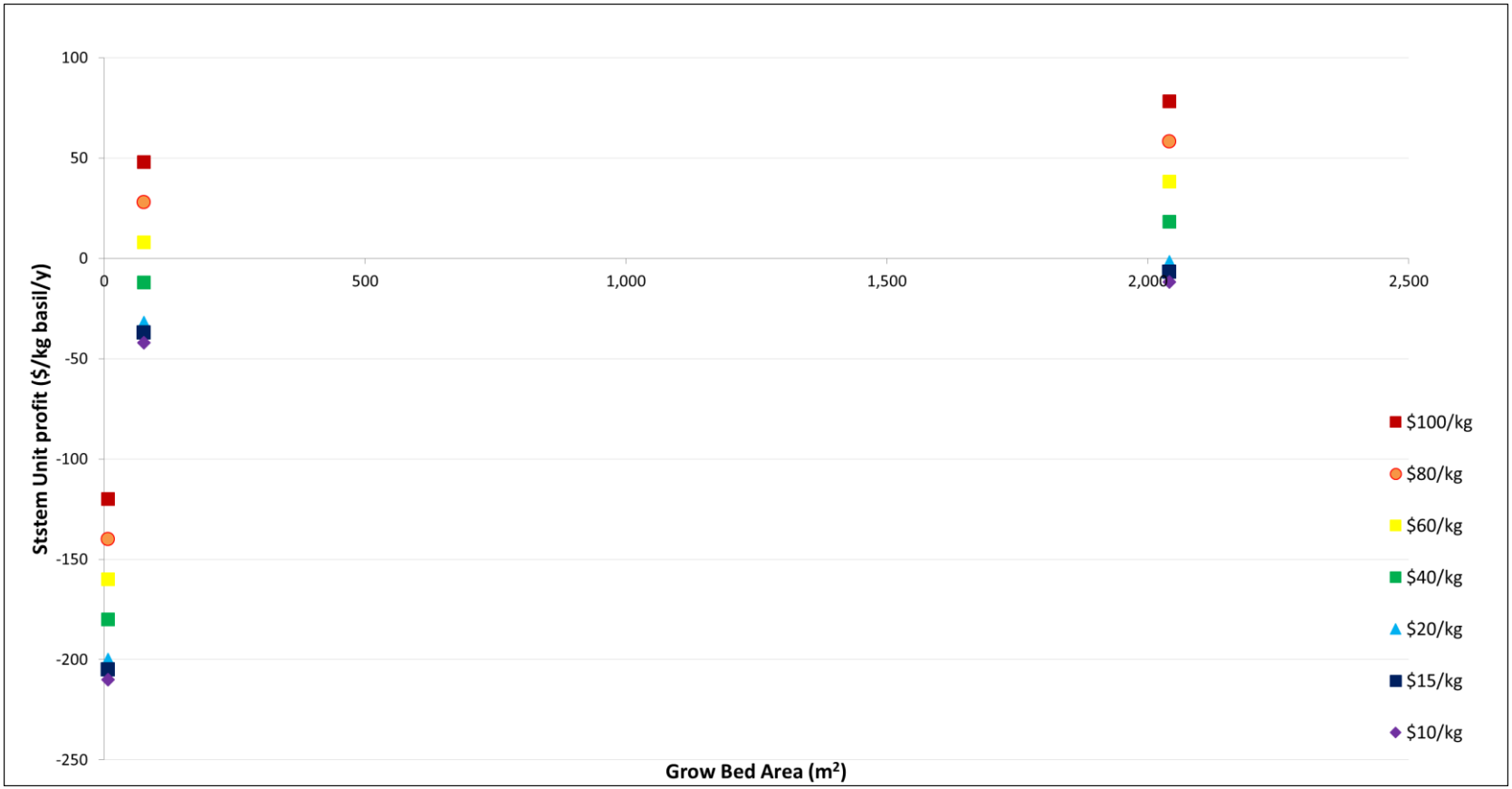

Figure 5.18. System unit profits with various basil prices of tilapia-basil aquaponic systems with various grow bed areas (for a given tilapia sales price: $9 /kg).

Figure 5.19 The Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

Figure 5.20 Basil in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

Figure 5.21 Tilapia in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

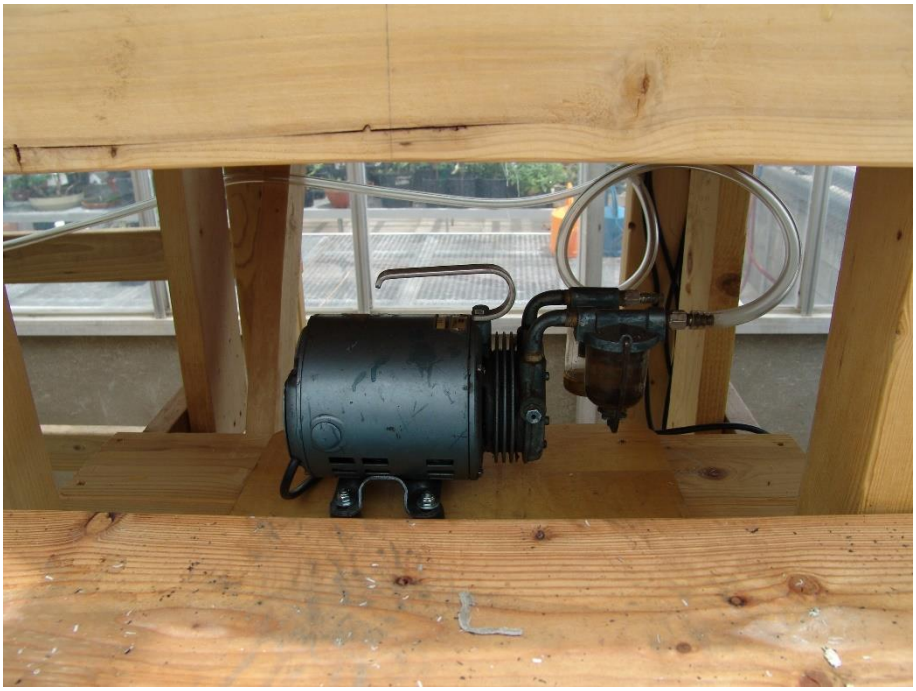

Figure 5.22 Blower in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

Figure 5.23 Fish tank and filter tank in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

Figure 5.24 Stock tank in the Iowa State University tilapia-basil aquaponics (courtesy of Allen Pattillo).

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

The major work conducted by the author included three parts: Distillers dried grains with solubles (DDGS) fractionation, Life cycle assessment (LCA) and Techno-economic analysis (TEA) of DDGS fractionation, and LCA and TEA of tilapia-basil aquaponics.

After being fractionated at the optimized parameters, the separation of fractions with high protein and high oil was obvious. Based on the nutrient component analysis and economic analysis, when the eccentric shaft vibration was 420 rpm, side slope of the gravity separator deck was 5^{o}, and the airflow rate was 0.8890 m/s, using size category of 0.425-2.000mm DDGS, the most benefit could be attained.

LCA and TEA were calculated based on the optimized DDGS fractionation. DDGS was firstly sieved into three size categories: >2.000 mm (over 10 mesh), 0.425-2.000 mm (10-40 mesh), and <0.425 mm (through 40 mesh); and then one category of 0.425-2.000 mm DDGS was further separated into light, mid-light, mid-heavy and heavy fractions using a gravity separator. The annualized total cost of DDGS fractionation increased as the scale expanded, and unit cost decreased as the scale expanded. In the lab scale, the profit was negative while in the pilot and commercial scale (with a processing rate of 864 t/y and above), the profit was positive.

Aquaponics is a relatively new biosystem which is considered as sustainable agriculture. There were some research focusing on its mechanism, nutrient cycle, and operation optimization. However, there was not much study about environmental and economic impacts for aquaponics located in the main land of U.S. Based on the information

acquired from literature and work experience, LCA and TEA were conducted for a research-scale tilapia and basil aquaponics located on Iowa State University, Ames, Iowa. The results showed that unit water and energy consumption and unit greenhouse gas emission decreased as the scale expanded, and both scale and basil price played important role in economic feasibility.

6.2 Conclusions

There were some methods had been explored to fractionate DDGS. The benefits of optimization of DDGS fractionation through a gravity separator included: easy to operate, efficient separation on protein and oil, and economic sustainable. When using the optimized parameters on gravity separator, high profits could be attained.

Both LCA and TEA showed the operation scale influence the economic feasibility for DDGS fractionation and for aquaponics. When the operation scale was large enough, it was possible to make profits. The unit environmental impacts decreased as operation scale expanded, which indicated that commercial scale biosystems had large potential to be economic sustainable.

6.3 Future Work

For the DDGS fractionation, the present work only conducted the study for one DDGS sample, more work needs to be done using various DDGS samples from different ethanol plants; and more gravity separator parameter combinations can be tested to improve the fractionation process.

For the LCA and TEA of DDGS fractionation through a gravity separator based on the optimized parameters, the future work should focus on evaluating DDGS fractionation processes through different sifters and gravity separators, and explore other DDGS fractionation process, to prompt DDGS fractionation in industry.

For the LCA and TEA of aquaponics, more work is required to conduct LCA and TEA for other types of aquaponics, such as using other fish and plant models instead of tilapia and basil, and using other system materials other than plastic fish tank and raft grow bed system.