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Sustainability analysis of soybean refinery soybean oil extraction process

by

Ming-Hsun Cheng

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural and Biosystems Engineering

Program of Study Committee:
Kurt A. Rosentrater, Major Professor
Carl J. Bern
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The student author and the program of study committee are solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred

Iowa State University

Ames, Iowa

2017

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DEDICATION

This dissertation is dedicated to my lovely families for their unconditional support and love. Thank you for being my most supportive backbone and encouraging me to chasing my dreams!

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ABSTRACT

Soybeans are one of the main sources of oil crops around the world. Soybean oil is the most common product of soybean refinery. It is a resource of edible oil and has other food and industrial applications.

Techno-economic analysis (TEA) is applied to estimate the economic feasibility of the soybean oil extraction process. The mechanical extruding-expelling process, hexane extraction, and enzyme assisted aqueous extraction process (EAEP) are analyzed. Total capital investment, operating costs, and revenues are the three basic indices for evaluating gross profit and net profit; which are general indicators of economic feasibility of a manufacturing venture. Additionally, cash flow analysis and sensitivity analysis are used to evaluate profitability while considering the net present value (NPV) and the driving force of manufacturing individually.

According to the analysis, the extruding-expelling process is a profitable and product-leading process as the scale of oil production is over 12 million kg of annual soybean production. In addition to soybean oil, soybean meal provides over 70% of total revenues, due to its proper nutrient content for livestock feed applications. Hexane extraction is also a profitable process when the scale is over 173 million kg of annual soybean oil production. Before EAEP can start to earn profits, the capacity must be scaled up to over 40 million kg of annual soybean oil production. Additionally, the enzyme recycling and moderate strategy of co-product handling are required. The co-product handling includes selling aqueous fraction and insoluble fibers derived from EAEP, as these materials can be used for further corn-soybean based bioethanol production.

Besides, environmental impact analysis is used to evaluate the potential environmental impact and greenhouse gas (GHG) emissions resulted from these three oil extraction processes. The environmental impacts are evaluated based on mass balance of the processing; and is used to calculate environmental indices. The potential GHG emissions are estimated according to the energy consumption of the process. Results show, the EAEP and extruding-expelling have similar general environmental impacts, while hexane extraction has the highest environmental impact because the organic solvent, hexane is used as medium to extract oil. GHG emission results show, the extruding-expelling process has the highest GHG emissions due to its lower oil recovery and high-energy requirements needed to squeeze oil out from soybeans. By contrast, hexane extraction has the lowest GHG emissions because of its high oil recovery. Though the pretreatment of EAEP requires high-energy consumption, higher oil recovery than extruding-expelling process results in lower GHG emissions than the mechanical process.

In addition to the oil extraction process, co-product, distiller's dried grain with solubles (DDGS), from the corn-soybean integrated bioethanol production is another main revenue source to increase profits for the whole refinery system. The combination of sieving and aspiration is used to fractionate DDGS based on the physical properties of nutrients, especially the density profile. Particle size of DDGS and the flowrate used in aspiration are the main variables for fractionation. The proper combination and interaction of variables for protein and oil separation are higher flowrate, smaller particle sizes, and heavy fraction. The best efficiency for protein and oil separation reaches about 29.7% and 68.15% respectively. For fiber separation, a mild condition results in higher fiber content approximately 7%.

CHAPTER 1

INTRODUCTION

The U.S. is the largest soybean producing country around the world, bringing over 34.5 billion dollars of profit in 2015 (SoyStats, 2016). Soybean refinery plays an important role in producing soybean-based products.

Soybean oil and protein are major products for food, livestock feeds, and industrial applications. Soybean oil extraction is generally the first step for further applications. As the world population grows and the demands of food and energy increase, various techniques have been developed; mainly focusing on how to improve the efficiency of extraction and product yields, regardless of the economic feasibility and sustainability of the technique or approach. This study focuses on the sustainability analysis; including the techno-economic analysis (TEA), environmental impact analysis (EIA), and critical parameters for increasing crop meal values of the soybean oil extraction processes. The conventional mechanical expelling and solvent extraction process are compared to the enzymatic assisted aqueous extraction process (EAEP), which is nominated for a corn-soy integrated biorefining process to produce biofuel and value added coproducts.

1. Soybean

Soybeans, *Glycine max* L., are one of the major crops planted in America. Soybeans are a traditional food source in Asia, and are widely believed to be originated in China about 4000 to 5000 years ago. Their early introduction to the U.S. can be traced back to the mid-eighteenth century, with the largest official introduction occurring in the early 1900s (Liu, 1997).

The word “soy” is derived from Japanese word “しょうゆ” pronunced as “shoyu”, and is generally used to make tofu, soy sauce, and miso in Asia. In the west, seed oil and meal are the two major products of soybeans due to its high oil and protein contents; which are about 18-23% and 35-45% individually (Hymowitz, 2008). Seed oil is not only a resource for cooking, but also for further food applications such as margarine, salad dressing, and mayonnaise. Soybean meal is mainly used in high protein feeds for livestock (Nelson et al., 1987). Soybean protein can also be extracted in the form of protein concentrates and isolates used for human consumption (Hymowitz & Newell, 1981).

Botanically, a mature soybean seed consists of three basic parts: the seed coat, cotyledons, and germ, or hypocotyls (Fig. 1-1). The seed coat, also called hull, holds two cotyledons together. The cotyledons are known as embryos, which function as food reserve structures. Generally, the soybean seed contains about 8% hull, 90% cotyledons, and 2% germ by weight (Perkins, 1995, Liu, 1997). Within the cotyledons, it is filled with palisade-like cells, which consist of oil and protein in the form of oil and protein bodies (Smith & Circle, 1972). Therefore, the cotyledons are the major part of a soybean seed which are used for further applications.

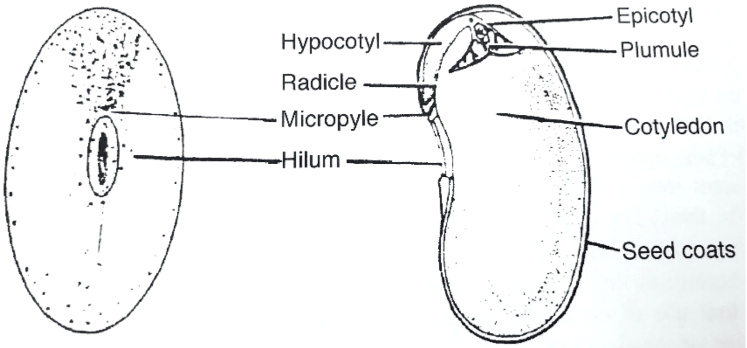

Fig. 1-1 Structure of soybean seed (Liu, 1997)

2. Soybean Refinery

In soybean refinery, extracting seed oil and concentrating protein contents are the main purposes. According to seed structure, removing the soybean hull is required for most processes. However, oil extraction is regarded as the first step of soybean applications.

Microscopically, oil is stored in spherosomes, also called oleosomes, which have a structure consisting of a triglycerol matrix core surrounded by a monolayer of phospholipids, and are embedded with oleosin-protein (Fig. 1-2). The portions of these three components are about 94%, 2% and 4% by weight respectively (Huang, 1994, Huang, 1996, Kapchie et al., 2008). For extracting oil from oil bodies, pressure, heat, organic solvents, and enzymes are usually used. In this study, mechanical expelling, solvent extraction, and ezymatic assisted aqueous extractions are investigated.

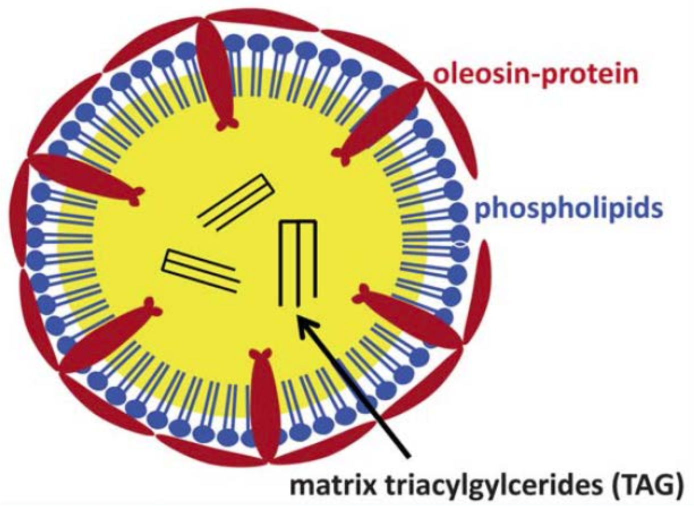

Fig. 1-2 Structure of oil body (Waschatko et al., 2012)

2.1 Mechanical Extruding-Expelling Process

The mechanical process is the original technique used to extract oil from seeds by applying pressure and heat to disrupt oleosome structure. In the early 1940s, hydraulic pressing and continuous screw pressing were the main techniques for oil extraction used in the U.S. (Markley & Gross 1944, Nelson et al., 1987). This typical process is now mainly used to produce oil for food and industial applications. Also, the cake collected from the mechanical process is the main resource for animal feeds.

However, the low efficiency of oil recovery is the main hurdle when using this process in the soybean industry. To improve oil recovery, higher cooking temperatures are required; which results in over-heating, darkening, and deterioration of oil. Nelson and his colleagues (1987) introduced an extruding-expelling approcah to reduce the disadvantages caused from excessive heating and increased the oil recovery rate to over 70%. According to the extruding-expelling process, an extrusion process replaces a heating process before expelling. The extrudate of coarsely ground whole soybean with 10-14% misture acts as a semi-fluid. Also, the short dwelling time in the extruder generates sufficient heat through the friction if soybean flakes (over 130^{o}C), to break the oleosome structure.

In the mechanical process, heat and pressure are the two main principles for extracting oil. Therefore, no chemical addition is an advantage of the expelling. However, high energy and facility maintenance requirements are still the problems of the mechanical pressing process.

As the crude oil is extracted, degumming, alkaline refining, bleaching and deodorization are the additional processes to produce refined oil for further food applications.

2.2 Hexane Extraction

Solvent extraction uses the solubility of oil and a nonpolar organic solvent to extract oil from soybean flakes. Compared to the mechanical expelling process, solvent extraction can remove about 0.5% of residual oil with less energy consumption and facility maintenance (Anderson, 2011). Due to its relatively higher oil recovery and energy efficiency, the development and application of solvent extraction has expanded since the 1940s along with the early expansion of U.S. soybean production (Woerfel, 1995).

Hexane is the solvent most used for oil extraction, and it is the mix of isomers with similar properties which is also called extraction hexane or commercial hexane (Anderson, 2011). Compared to *n*-hexane, extraction hexane has similar molecular weight and specific gravity, higher ignition and flash temperature, lower melting point and boiling point Table 1-1 (NFPA-36 standard, 2009). These properties increase the safety of operating. Additionally, the extraction hexane results in a slightly greater ability to extract efficiently than *n*-hexane, due to the presence of various isomers.

Table 1-1 Physical properties of n-hexane and extraction hexane (NFPA-36 standard, 2009)

Property	n-hexane	Extraction hexane
Ignition temperature (^oC)	225	264
Flash point (^oC)	-26	-18
Molecular weight	86.2	86.2
Melting point (^oC)	-94	-154
Boiling range at 1atm (^oC)	67-69	56-60
Specific gravity at 15.6 ^oC (kg/L)	0.68	0.66
Vaporization at 1atm (kcal/kg)	79.6	N/A
Vapor pressure at 37.8^oC (kPa)	38.1	39.4

In solvent extraction, it includes bean cleaning, drying, cracking, dehulling, flaking, solvent extraction, and meal handling (Fig. 1-3). Cleaning removes foreign matter and is important for protecting equipment and producing high-quality products. After cleaning, beans are dried, leaving 10% of the bean's moisture for dehulling by an aspirator. Before dehulling, proper cracking is necessary. In the cracking and dehulling processes, moisture content plays an important role in determining the effiency of hull removal. If the beans are too dry (<10% moisture), they are easier to pulverize in the cracker and resultin excessive fines. The hulls are hard to be removed when the beans are too moist (>10% moist). The conditioning process is conducted after dehulling. In the conditioner, the cracked beans are heated to about 71°C, and the moisture content is adjusted to around 11% by steam or a water spray, making the beans plastic for flaking. Flaking mainly used increases the surface area of soybean flakes to obtain higher oil recovery. A flaking mill consists of a pair of smooth-surface rolls driven at different speeds. The desired flake thickness is generally 0.2 mm to 0.5 mm. The processes above are seen as preparation steps for the following extraction process (Woerfel, 1995).

During extraction, an immersion type extractor was first developed, and the ratio of solvent to beans are 5~10:1 typically. The large amounts of solvent lead to higher material costs and some safety issues. The percolation extractors reduce the ratio of amounts of hexane to beans in extraction to about 1:1, and increase the efficiency of oil extraction. The percolation refers that the solvent passes down through the porous bed of oil-bearing material, the oil is then dissolved in the solvent and carried alway (Woerfel, 1995, Pramparo et al., 2002). Generally, continuous loop extractors (Crown Iron Works, 2016), belt extractors (Extraction de Smet, 2016), and rotary Rotocel® reactors (Becker, 1978) are the three major types of percolation extractors, which are applied in large scale, continuous operations.

After extraction, solvent recycling is necessary to ensure oil is safe. The recycled solvent is reused for further ectraction. Steam and vacuums are used to remove hexane, with the temperature determined by the flash point of crude oil, which is when the flame briefly appears over the crude oil. The temperature is generally set at 121°C for refined soybean oil corresponding to the 1000 ppm hexane in the oil (Anonymous, 1993, Proctor, 1997). The degumming process (Dijkstra, 2011) produces degummed crude oil, which is sold as a commodity.

For soybean meal handling, a toaster is used to remove the remaining hexane. Steam is also used to evaporize hexane and to heats the protein to 100-105°C; enhancing the nutritional value by inactivating trypsin inhibitors and other toxicants. After the toasting, the hot air dries the meal reducing its moisture to about 10%. The defatted meal is ground and screened to a desired particle size for further applications (Hettiarachcy & Kalapathy, 1997).

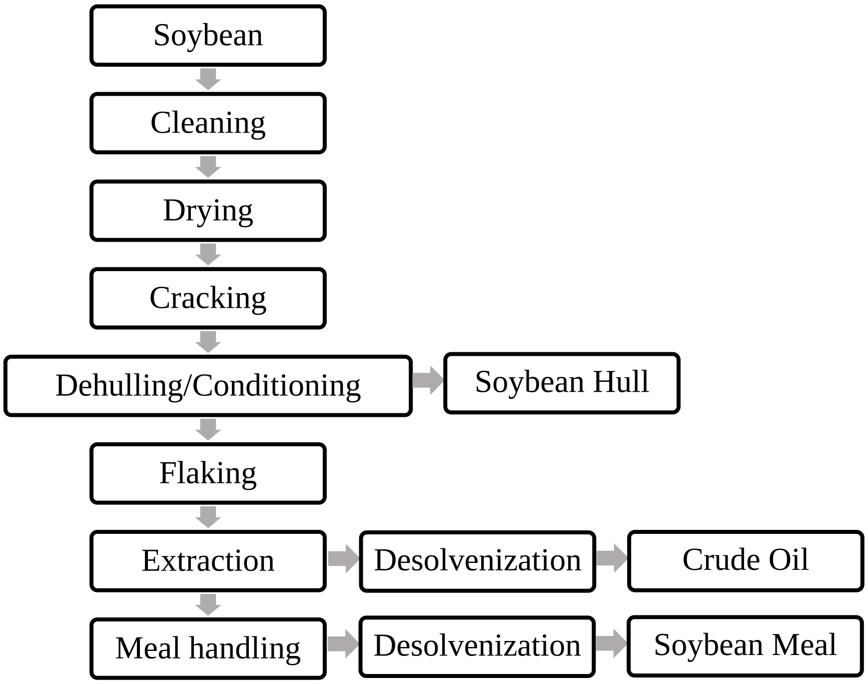

Fig. 1-3 Schematic flow of oil solvent extraction

2.3 Enzymatic Assisted Aqueous Extraction (EAEP)

According to the convential processes, low oil recovery, environmental, and safety problems derived from organic solvents are the main disavantges of mechanical expelling and solvent extraction respectively. Aqueous extraction was introduced as an alternative in the 1950s (Rosenthal et al., 1996). Water is used as the solvent in the process, which reduces cost and improves safety issues.

Based on the structure of oil bodies stored in the cotyledons (Fig. 1-1), they are stabilized by proteins called oleosins. The structure of olesins cosist of three basic domains: (1) the amphipathic domain present at the amino terminus, associated with oil body surface; (2) the central hydrophoic domain, which interacts with the triglycerides matrix of oil bodies; and (3) the amphipathic domain at or near to carboxyl terminus, which interacts with the phospholipid surface (Murphy, 1993, Beisson et al., 2001). Therefore, proteases are commonly used in the aqueous process to improve oil yield (Zhang et al., 2013). This improved aqueous extraction process is defined as enzymatic assisted aqueous extraction process (EAEP).

In EAEP, the preparation of soybean flakes is similar to solvent extraction and the schematic flow is illustrated in Fig. 1-4. Adequate pretreatment, which not only disrupts the soybean tissue but increases the porosity of flakes, is used to increase oil yields to over 80% (Domiguez et al., 1996, Rosenthal et al., 1996). Extrusion (Jung & Mahfuz, 2009), ultrasonication (Shah et al., 2005), microwave heating (Valentova et al., 2000), ohmic heating (Pare et al.,2014), pulsed electric fields (Guderjan et al., 2007) etc. have been introduced to combine with aqueous extraction to improve oil recovery.

In the aqueous extraction process, enzymes are added to assist the release of oil bodies. After the extraction, the system forms two fractions: cream and skim. Centrifuge is used to separate cream phase and aqua phase (Skim I). When the oil is extracted, it forms a stable emulsion in the cream phase due to the presence of proteins, which act as emulsifiers (Nylander et al., 1997). Thus, the protease is also used in the demulsifying process to hydrolyze the interfacial proteins (de Moura et al., 2011, Yusoff et al., 2015). The protease functions to reduce protein molecular size, rigidity of oil droplet surfaces, and remove high molecular weight polypeptides to release free oil. Free oil can be separated by the centrifuge, and the protein collected from skim II (Chabrand et al., 2008,Chabrand and Glatz, 2009).

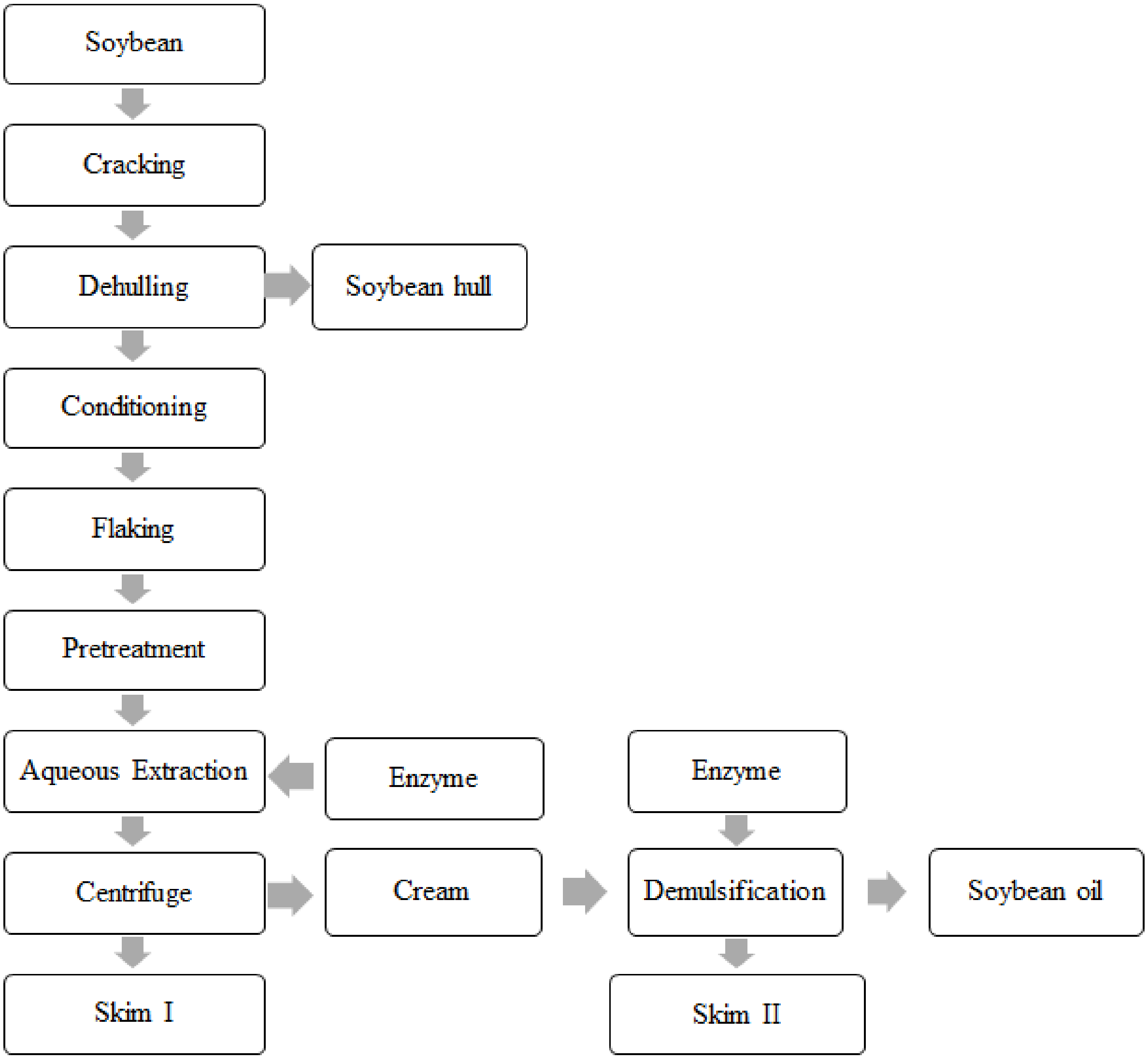

Fig. 1-4 Schematic flow of enzymatic assisted aqueous extraction process

The EAEP technique uses the isolubility of water and oil rather than the principle of solvent extraction. Additionally, the proteins are extracted simultaneously, resulting in low phospholipid content. Also, the further refinery processes, such as degumming, can be eliminated (Jung et al., 2009). Thus, the EAEP is regarded as a chemical free approach for oil extraction; which not only improves oil recovery compared to the expelling process, but prevents environmental and safety problems resulting from solvent extraction process.

3. Sustainability Analysis

As new technology is invented and developed, sustainability is important for making the new processes practical in operation. The concept of sustainability has been widely dicussed since the mid 1980s, according to the Brundtland Commision (1987). The main spirit of the discussion is "development that meets the needs for the present without compromising the ability of future generations to meet their own needs.". Generally, sustainability control is driven by economic, environmental and social development. In the enginnering fields and the production lines, the economic feasibility and environmental impacts are main concerns.

3.1 Techno-Economic Analysis (TEA)

Economic feasibility is the index which reflects whether the process applies in the industry directly. The techno-economic analysis (TEA) is used to evaluate the potential profits of a process. For soybean processing, the TEA estimates the profitibility of soybean-based fuels (Haas et al.,2006, Marchetti et al., 2008, Apostolakou et al., 2009) and chemicals (Ngo et al., 2014). Capital investment, operating costs and revenues are the major parameters to estimate the profit of the processing (Fig. 1-5).

Capital investment indicates facility related costs; which are the capital necessary for the installed process equipment with all components for complete process operation (Peters et al., 2003). That includes direct, indirect, contractor and contingency, working capital, and startup costs. The equipment purchasing fees are the basis for the estimation of capital investment. Direct cost is the fees assessed when installing purchased equipment, including installation, piping, instrumentation, insulation, electrical systems, building, yard improvement, and auxiliary facilites. These costs cover the expenses for labor, materials, and supplies used to connect each operating unit, power wiring, construction, utility system, and even the transportation system within the plant (Peters et al., 2003, Heinzle et al., 2006).

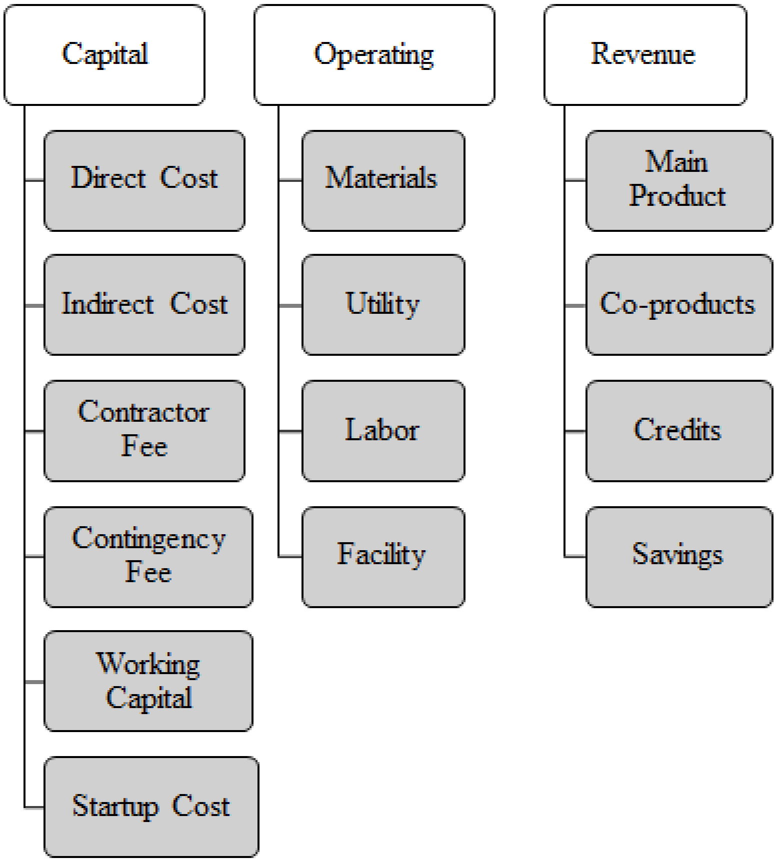

Fig. 1-5 Parameters for profit estimation

Indirect cost includes engineering and construction fees. These expenses are mainly projects, equipment, control systems, computation designs, and the temporary construction and operation at the construction site. Contractor's fees and contingency are also included in capital investment; with the contingency covering expenses for unexpected events such as storm, floods, small design changes, errors in estimation, and other unforseen events and expenses (Peters et al.,2003). Before a plant starts to operate, startup capital is the additional cost to validate the facilities and production line. Finally, working capital is invested to make sure material supplies, product storage and handling, account recievable and payable, cash for payments, and taxes payable are available. These costs are estimated by multiplying the total machine purchasing cost with the multiplier. Multipliers used in typical chemical and enzymatic processes are shown in Table 1-2 (Peters et al., 2003, Heinzle et al., 2006).

Table 1-2 The multiplier for estimating capital investment for chemical and enzymatic process (Heinzle et al., 2006)

		Mulitpliers	
Costs	Categories	Minimum	Maximum
Total Plant Direct Cost (TPDC)	Purchase cost (PC)		
	Installation	0.25×PC	0.55×PC
	Process piping	0.30×PC	0.80×PC
	Instrumentation	0.08×PC	0.50×PC
	Insulation	0.08×PC	0.09×PC
	Electrical	0.10×PC	0.40×PC
	Buildings	0.10×PC	0.70×PC
	Yard improvement	0.10×PC	0.20×PC
	Auxiliary facilities	0.40×PC	0.10×PC
	TPDC	1.40×PC	4.20×PC
Total Plant Indirect Cost (TPIC)	Engineering	0.05×TPDC	0.30×TPDC
	Construction	0.30×TPDC	0.55×TPDC
	TPIC		
Total Plant Cost (TPC)	TPDC+TPIC		
Contractor’s fee and Contingency (CFC)	Contractor’s fee	0.03×TPC	0.08×TPC
	Contingency	0.05×DFC	0.15×DFC
Direct Fixed Cost (DFC)	TPC+CFC		
Working Capital (WC)		0.10×DFC	0.20×DFC
Startup Capital (SC)		0.03×DFC	0.08×DFC
Total Capital	TPC+CFC+WC+SC		

Operating costs consist of material, labor, utility, and facility related costs. These costs change with the fluctuation of market and economic conditions. Also, operating costs can be estimated by plant capacity, efficiency of processing, and operating conditions. The raw material cost is seen as the major cost in production and refers to materials directly consumed in making the final products, and chemicals or enzymes used to improve productivity. Besides market and economic conditions, raw material costs change proportionally with the capacity of the plant (Ulrich, 1984, Peters et al., 2003). Utility cost, including elctricity, steam, cooling water, natural gas, and other heat exchange agents are other critical resources for operating costs. Operating cost also depends on the amount of material handling and product yields, and varies based on different plant locations. However, it generally takes about 10-20% of total product cost in a chemical process (Peters et al., 2003).

The facility related costs refer to the expenses for machine maintenance. Labor cost can be divided into labor-dependent cost and laboratory quality control and assurance cost (Heinzle et al., 2006). Operating labor is then divided into skilled and unskilled labor. The expense for laborers is estimated by hourly wage rates; however, it also varies based on different industries and plant locations. Laboratory quality control and assurance cost is generally estimated by taking 10-20% of the total labor-dependent costs in a chemical plant (Peters et al., 2003, Heinzle et al., 2006).

Compared to total capital investments and operating costs, revenues obtained from processes are easier to estimate; which is the product of produced amounts and selling prices. According to total capital investments, operating costs, and revenues, the gross profit and net profit can be calculated. Those calculations are indexed and used for evaluating the profitability of the process.

3.2 Environmental Impact Assessment

Environmental issues have been attracting many concerns because the concept of global warming and energy conservation is advocated by many groups. The life-cycle assessment (LCA) is the method used to assess the environmental impact for a product; including material generation, processing, energy supply and consumption, product end-use, and waste handling. Therefore, it is also regarded as a "cradle-to-grave" assessment methodology. The development of LCA can be traced back to the 1970s (Guinée et al., 2011).

To have a well-rounded LCA study, a lot of data is needed for the analysis. However, there are still difficulties to collect detailed data for a well-rounded LCA. Therefore, a proper screening and streamlined method is needed for LCA studies (Bretz & Frankhauser, 1996, Weidenhaupt & Hungerbühler, 1997). Other research uses different methods for environmental assessment such as the waste reduction algorithm (Young et al., 2000) and the quantitaive environmental impact analysis (Elliot et al., 1996, Heinzle et al., 1998). The following environmental quotient was introduced by Sheldon (1994): (EQ)=E×Q, where E indicates the environmental factor of the amount of waste, and Q represents the environmental unfriendness of the produced waste. This concept innovates the way main origins of waste are indentified and how they result in the plant's environmental impact.

Heinzle's research group introduced a quantitative method in 1998 to assess the environmental impact caused by processing plants. Mass flow is the basis for the calculation of environmental indices. The whole process is divided into input and output components. The input component indicates every material used for making products; while the output component represents the products and wastes derived from operations. According to mass balance in processing, the mass flow is converted into the mass index. Also, each component is classified into different categories (A, B, and C) based on their toxicity, polution, and global warming potentials. The environmental impact of the process is assessed by these two main parameters; which also correspond to the environmental quotient “E” and “Q” respectively (Fig. 1-6).

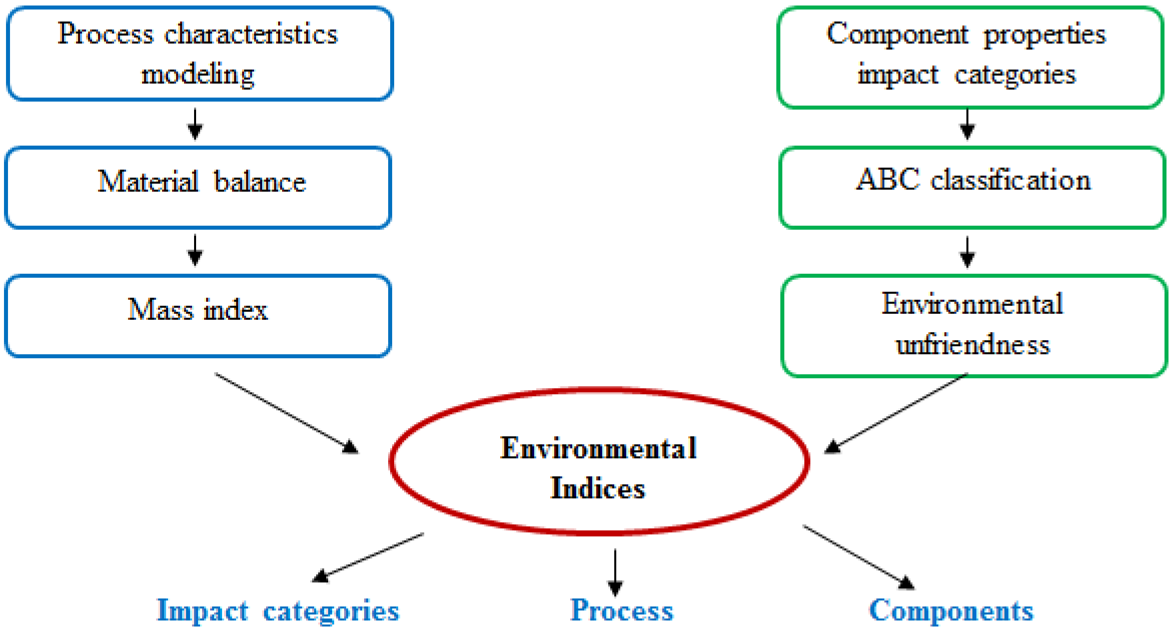

Fig. 1-6 The framework of environmental indices for environmental impact analysis (Heinzle et al., 2006)

When the environmental indice of each component is combined, the general environmental impact of the total process can be evaluated. Because the environmental indices of each component are calculated separately, the “hot spot” operating unit and component of the processing are able to be observed. However, unlike the complete LCA, this quantitative method for environmental impact assessment does not include energy consumption. Therefore, the GHG emissions resulting from energy consumption in processing such as electricity, steam, natural gas are evaluated separately (Heinzle et al., 2006).

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CHAPTER 2

OBJECTIVES

The corn-soybean integrated biorefinery is a developing system, which could increase the biofuel yields and improve the economic values from products. The overall objective of this study focuses on the sustainability analysis of soybean oil extraction processes, including economic feasibility and environmental impact analysis. Additionally, the effectiveness of the DDGS fractionation from the bioethanol production is investigated as well.

More specifically, the sub-objectives of this study were:

1. Building up a techno-economic analysis (TEA) model to evaluate the economic feasibility of mechanical expelling technique: The extruding-expelling process.
2. Building up a TEA model to evaluate the economic feasibility of typical solvent extraction technique: The hexane extraction.
3. Building up a TEA model to evaluate the economic feasibility of a solvent free technique: The enzyme assisted aqueous extraction process (EAEP).
4. Using Cash flow analysis to evaluate the profitability of these three soybean oil extraction processes.
5. Performing sensitivity analysis to test the driving force of these three soybean oil extraction processes.
6. Conducting the environmental impact analysis (EIA) to evaluate the potential environmental impacts and greenhouse gas (GHG) emissions of these three soybean oil extraction processes.

7. Testing the efficiency of distilled dried grains with solubles (DDGS) fractionation by sieving and aspiration.

   (H_o: Combination of sieving and aspiration could improve the DDGS nutrient fractionation).

CHAPTER 3

TECHNO-ECONOMIC ANALYSIS OF SOYBEAN OIL EXTRUDING-EXPELLING PROCESS

Modified from a paper to be submitted to *Industrial Crops and Products*

Abstract

Mechanical expelling is a conventional technique used to extract soybean oil; but because of its lower oil recovery, solvent extraction is applied more in industry. However, there are some plants using extrusion before the expelling process to improve final oil recovery. Additionally, the mechanical process is still used due to specific purposes such as livestock feeds applications. SuperPro Designer was used to perform a techno-economic analysis (TEA) of the extruding-expelling process. Soybean oil is the main product being sourced from processing, despite soybean meal contributing over 75% of total revenues. Compared to the general solvent extracted meal, expelled meal has a higher selling price due to its higher oil content of about 10%. Through fluctuation of economic conditions, soybean meal still plays an important role in earning profits, making the whole mechanical profitable, especially when the capacity is scaled up to 12 million kg of annual soybean oil production. Therefore, soybean meal has been regarded as the driving force for the mechanical expelling process.

Keywords: Techno-economic analysis, Extrusion-expelling process, Soybean oil, Soybean meal, Profits

1. Introduction

Soybean (*Glycine max* L.) is the main oil crop in America, and production has increased over 50% to about 3.93 billion bushels since the 1980s (SoyStats, 2016[a]). Iowa is one of the major states producing soybeans (SoyStat, 2016[b]). The value of soybeans include good quality oil and digestible proteins and minerals (Lynch et al., 1987, Corley et al., 1999, Sawada et al., 2014).

Soybean oil is the main product of soybean processing. It is also the main oil used for applications in the food industry and industrial applications, such as biodiesel and biolubricant conversion (Ma & Hanna, 1999, Erhan & Asadauskas, 2000). Soybean meal is also an important product from the oil extraction process, and is used as a protein source in livestock feed due to its well-balanced amino acid profile, relatively high crude protein level, and variety of minerals and vitamins (Cheng and Hardy, 2003).

Mechanical and solvent extractions are two major approaches used in the soybean processing industry and use expeller and extraction hexane. The mechanical process, with hydraulic pressing and continuous screw pressing techniques, was used before the development of solvent extraction (Nelson et al., 1987). Since higher oil recovery efficiency derived from solvent extraction, mechanical expelling has been mostly replaced by the solvent extraction technique. However, the organic solvents used in extraction causes saftey and environmental related issues (Li et al., 2004, Oliveira et al., 2013). Therefore, a chemical free process, known as the expelling approach is still applied when producing oil for food and industrial purposes. Also, soybean meal produced from the expelling process is still used predominantly for animal feeds (Nelson et al., 1987).

Typically, cracking and cooking are used to reduce crop size and disrupt spherosomes tissues first, before pressure is applied to squeeze oil out of the matrix (Erickson, 1995). For increasing oil recovery, several passes of pressing are needed. However, multiple passes lead to excessive heating, resulting in darkening and deterioration of oil. Nelson et al. (1987) introduced an extruding-expelling process (Fig. 3-1), where an extrusion is performed before the expelling process. The cooking process is also exempt from processing beacuse the heat is generated from the friction among beans within extruders. This technique not only simplifies the tissue rupturing and heating processes, but increases the oil recovey to over 70%. This approach is also used in the soybean oil expelling industry.

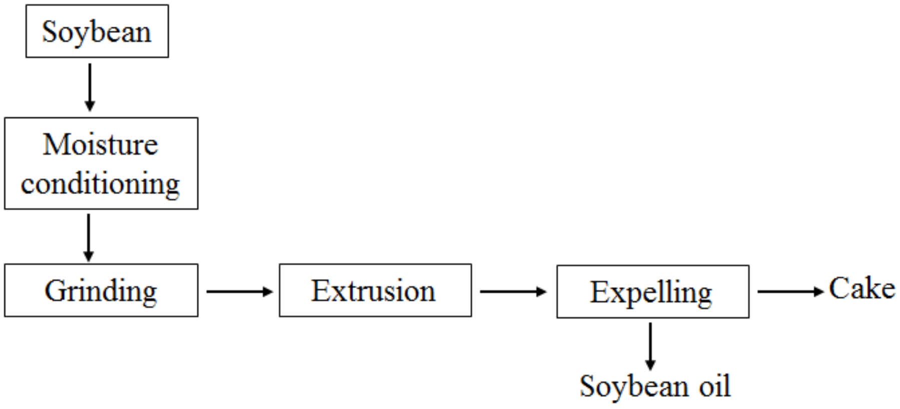


Fig. 3-1 Flow diagram of extruding-expelling process

Researchers perform different pretreatments and parameters to expelling to try and improve oil recovery from the expelling process (Bargela et al., 1999; Patil and Ali, 2006; Subroto et al., 2015). However, economic parameters are critical factors for the mechanical expelling technique due to industrial and commercial applications. The study of oil extraction economic analysis is generally included in biodiesel production techno-economic analysis, because oil extraction is regarded as a part of the pretreatment of biodiesel conversion (Nelson et al., 1994; Haas et al., 2006; Marchetti et al., 2008). Also, the different methodologies of economic modeling are conducted for vegetable oil use in biodiesel conversion (Bender, 1999; Zhang et al., 2003;

Mlay et al., 2014). However, few studies' main focuses are economic parameters and feasibility of oil extraction, especially for mechincal expelling.

This study focuses on the extruding-expelling process for degummed crude soybean oil production. Capital investment, operating costs, revenues, and profits are the main economic parameters for the analysis. Addtionally, historical data is collected and used to perform economic feasibility comparisons for different time periods from the 1980s to the recent year. Due to the increasing demand for energy and food, many processing plants are planning to scale up the capacity of their product lines. Therefore, the effects of different scales, from pilot scales to commercial scales, on the extruding-expelling process were also performed. The goal of this study is to build an economic model to estimate the potential capital investment, operating costs, and profits, and trying to project the relationship between the unit production cost and different operating capacities.

2. Materials and Methods

2.1 Extruding-Expelling Process

The extruding-expelling process is divided into crop handling, pre-extruding, expelling, degumming and oil recovery, and soybean meal handling (Fig. 3-2). In crop handling, soybean cleaning, drying, and grinding are included and the moisture content of soybeans are controlled to stay between 10-12%.

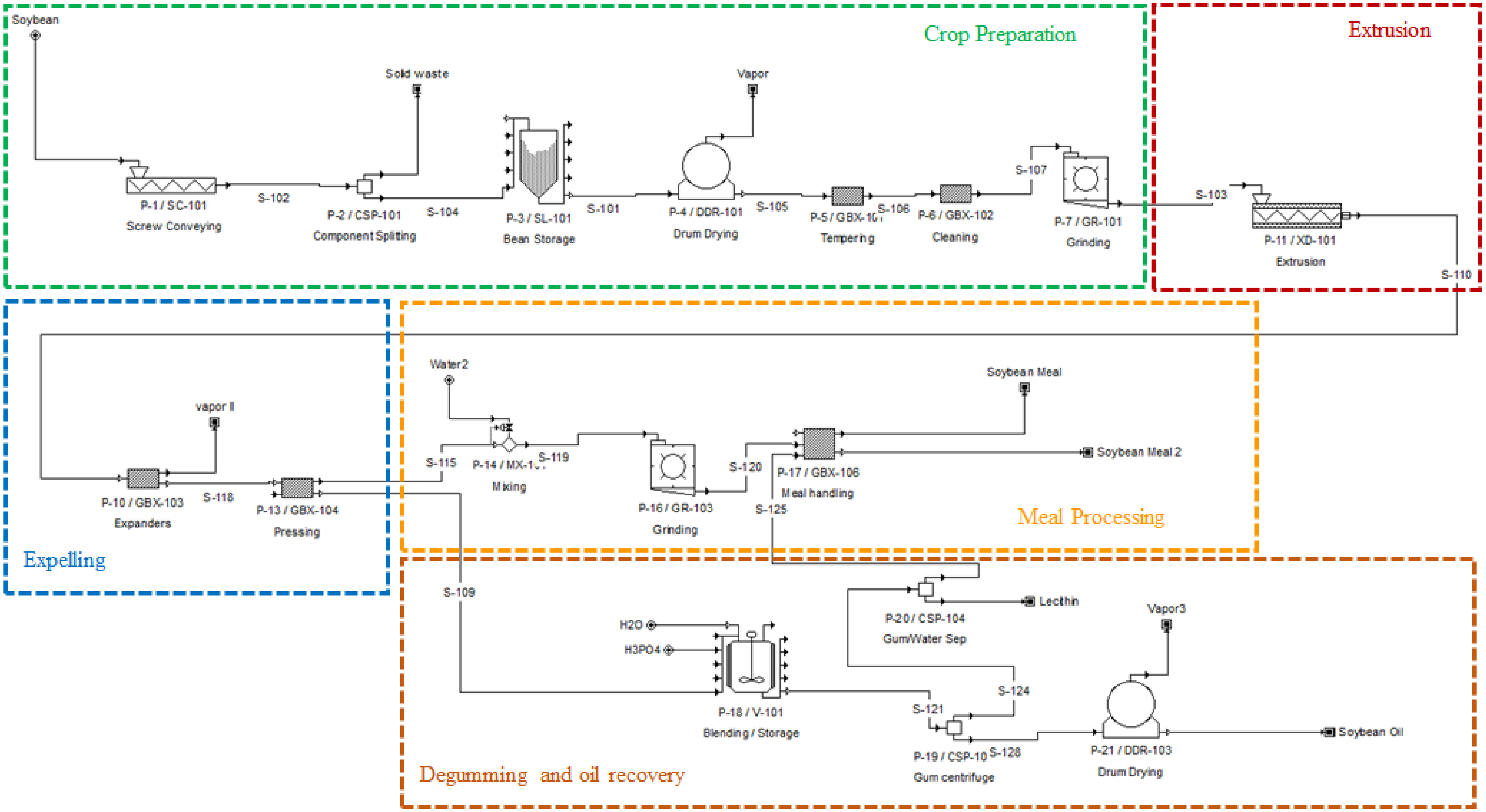


Fig. 3-2 Soybean oil extruding-expelling process

The pre-extruding follows crop handling. Different from typical conventional expelling processes, there is no need for cooking before expelling in the extruding-expelling process. During the extruding process, heat is generated during extrusion because of friction among beans. The short retention time for beans staying in the extruder is sufficient to break spherosome tissue, and the output temperature of the extruder is over 130°C (Nelson et al., 1987). After the pre-extruding, the extrudate of coarse ground whole soybean is at 10% to 14% moisture lecel, has the semi-fluid like property needed, and is transported to the expeller continuously.

In the expelling process, pressure is used to squeeze oil out of the matrix. The cake and oil are collected for further meal handling and degumming processeses respectively. Water degumming is applied to remove most parts of phospholipids. The amount of water used in the degumming process corresponds to the content of phospholipids with a 1:1 ratio by weight (Dijkstra, 2017). Also, phosphoric acid is used to remove small amounts of remaining water insoluble phospholipids. An 85% phosphoric acid solution is used, and the amount is 0.1-0.3% of phospholipid content (Deffense, 2017). After the degumming process, the oil is separated by a centrifuge and the oil is degummed crude oil.

The cake separated during the expelling process is collected and its moisture is kept below 10% for the convenience of storage. The cake is as well as called as soybean meal, which is the co-product of oil extraction and sold as livestock feeds.

2.2 Computer Modeling

The economic model of the extruding-expelling process for soybean oil production was performed by SuperPro Designer v9.0 (Intelligen, Inc., Scotch Plains, NJ). The simulation was conducted based on mass balance. Economic parameters including capital investment, operating costs, gross profit and net profit were evaluated according to model simulation (Ngo et al., 2014).

Based on the economic model of soybean oil based biodiesel production performed by Haas' et al., (2006), the capacity of 192.28 million kg annual soybean input was set as the referred scale for the simulations of different operating capacities, which are 30.77, 96.14, 672.99, 1257.53 and 2991.93 million kg of annual soybean inputs. The oil recovery efficiency is 72%, which results in the annual soybean oil productivity corresponding to these six scales as 4.10, 12.81, 25.62, 89.67, 175.56 and 398.67 million kg individually. Additionally, the different economic conditions from the 1980s to the recent year were also performed according to the referred scale. Historical data of operating costs were used as inputs for economic parameter estimations.

Fifteen years of plant life time, 30 months of construction, four months of startup period, 35% income tax ,and a ten year depreciation period with 5% salvage value of directed capital investment were set as general assumptions for the producing stream (Haas et al., 2006).

2.3 Assumption and Data Collection

2.3.1 Fixed Costs

The facility for each operating unit is the main resource of fixed costs. There are three main parts for fixed costs: total plant direct cost (TPDC), total plant indirect cost (TPIC), and contractor's fees and contingency (CFC). TPDC comes from the facility directly, including machine installation, piping connection, and electrical; TPIC is fees associated with engineering and construction, making the producing stream function. The basic total plant cost (TPC) is the summation of TPDC and TPIC. Additionally, the CFC is estimated by TPC; and the total direct fixed cost (DFC) is the summation of TPC and CFC. Howerver, the working capital (WC) and startup costs (SC) are fees to make sure the producing stream produces the product properly. Therefore, the total capital investment is the summation of DFC, WC, and SC. These costs are estimated by the facility purchasing fee with certain multipliers shown in Table 3-1 (Heinzle et al., 2006).

Table 3-1 Multiplier for directed cost and total capital investment estimation

Costs	Categories	Multipliers*
Total Plant Direct Cost (TPDC)	Purchase cost (PC)	
	Installation	0.47×PC
	Process piping	0.68×PC
	Instrumentation	0.26×PC
	Insulation	0.08×PC
	Electrical	0.11×PC
	Buildings	0.18×PC
	Yard improvement	0.10×PC
	Auxiliary facilities	0.55×PC
	TPDC	2.43×PC
Total Plant Indirect Cost (TPIC)	Engineering	0.30×TPDC
	Construction	0.35×TPDC
	TPIC	
Total Plant Cost (TPC)	TPDC+TPIC	
Contractor’s fee and Contingency (CFC)	Contractor’s fee	0.06×TPC
	Contingency	0.08×DFC
Direct Fixed Cost (DFC)	TPC+CFC	
Working Capital (WC)		0.15×DFC
Startup Capital (SC)		0.05×DFC
Total Capital	TPC+CFC+WC+SC	

The purchasing cost (PC) of each operating unit used for evaluating different investment years and plant capacities were adjusted and estimated by the inflation index (Eq. 1) (BLS, 2016[a]) and the six-tenths rule (Eq. 2) (Ulrich, 1984, Peters et al., 2011) individually. P_c is the inflation-adjusted price of equipment in the current year, P_p indicates the cost of equipment in the previous year, and I_c and I_p are inflation index factors of current and previous years separately. For the six-tenths rule (n=0.6), PC_p and PC_c are facillities’ purchasing cost of predicted and basis scales; q_p and q_c indicate the facilities’ capacity of predicted and basis scales respectively as well. However, the power (n) is varied from 0.4-0.8 depending on different types of machines used.

$$P_c = P_p \times \left(\frac{I_c}{I_p}\right) \qquad Eq.1$$

$$PC_p = PC_c \times (\frac{q_p}{q_c})^n \qquad Eq.2$$

The PC was collected from the SuperPro Designer database, inventory record of Center for Crops Utilization, Iowa State University, and the Haas' study (2006). The PC and the power use in this model are listed Table 3-2.

Table 3-2 Facility prices and power (n) used for PC estimation of different capacities (2015 price)

	Power (n)	PC of referred scale (thousands dollar)
Conveyor*	0.6	9
Storage bin*	0.6	1400
Drum dryer+	0.4	68
Grinder+	0.6	171
Extruder●	0.6	275
Expller+	0.6	1410
Degumming tank●	0.49	67
Centrifuge●	0.49	468
Dryer for oil recovery+	0.4	28
Meal grinder+	0.6	89
Meal processer+	0.49	2590

Date adjusted according to SuperPro Designer database (*), Haas' research (+) and Iowa State University CCUR pilot inventory record (●).

2.3.2 Operating Costs

Operating costs include material, utility, labor, and facility related costs. In the extruding-expelling process, the material cost is from soybeans, water, and phosphoric acid. Utility costs include electricty for operating machines, cooling water, and steam used as heating exchange agents. Agricultural machine operators and extraction workers are the main souces of labor costs. The operating costs inputs are presented as an average price of each 10 years and listed in Table 3-3. Additionally, the energy consumption inputs are listed in Appendix Table A-1.

Table 3-3 Operating costs inputs

		Unit	1980s	1990s	2000s	2010s	Citation
Materials	Soybean	$/kg	0.228	0.217	0.255	0.438	USDA ERS, 2016
	Phosphoric acid	$/kg	0.6	0.6	0.6	0.6	SuperPro Database
	Water	$/L	0.001	0.001	0.001	0.001	City of Ames, 2016
Utility	Electricity	$/kwh	0.047	0.047	0.057	0.066	US EIA, 2016
	Steam	$/MT	12	12	12	12	SuperPro Database
Labor	Ag. machine operator	$/hr	6.36	8.77	10.19	13.12	BLS, 2016[b]
	Extraction worker	$/hr	9.30	13.72	17.69	20.86	

For estimating labor costs, an agricultural machine worker was assigned to crop and meal handling; while extractor workers mainly dealt with the extruding-expelling process, degumming, and oil recovery processes. The labor requirement for each machine was set between 0.1-1 (workers/unit/ shift) for the referred scale, which is listed in Table 3-4. A shift presents 8 hours working time. Additionally, a 0.2-0.25 power relationship was applied to estimate the labor requirement for different operating capacities, and the expression is similar to Eq. 2 (Peters et al., 2011). Besides, the laboratory quality control and assurance cost were also considered and estimated by 15% of total labor cost (TLC) (Heinzle et al., 2006).

Table 3-4 Labor requirement for each operating facility (workers/unit/shift)

	Soybean Annual Input (million kg)					
	30.77	96.14	192.28	672.99	1527.53	2991.93
Conveyor	0.22	0.23	0.25	0.30	0.3	0.35
Storage bin	0.08	0.08	0.1	0.12	0.14	0.17
Drum dryer	1	1	1	1.26	1.46	1.82
Grinder	0.5	0.7	1	1.1	1.28	1.6
Extruder	0.88	0.95	1	1.1	1.16	1.24
Expeller	0.63	0.84	1	1.37	1.59	1.97
Degumming tank	0.64	0.84	1	1.35	1.6	1.96
Centrifuge	0.64	0.85	1	1.38	1.63	1.97
Dryer for oil recovery	0.8	0.8	0.8	0.8	0.8	0.8
Meal grinder	0.5	0.67	0.8	1.07	1.25	1.5
Meal processer	0.22	0.3	0.35	0.47	0.55	0.66

2.3.3 Revenues

Soybean oil and soybean meal are the products of the production stream. The selling prices from the 1980s to the recent year are also presented in the average price of each 10 years (Table 3-5). Additionally, the selling price of expelled meal is higher than the selling price of solvent extracted meal about $0.17/kg based on commodity price (USDA ERS, 2016, Quote from the Brekke's Town & Country Pet Supply, Ames, IA).

Table 3-5 Selling prices of products from soybean oil hexane extraction process

	Unit	1980s	1990s	2000s	2010s	Citation
Soybean oil	$/kg	0.49	0.50	0.62	0.94	USDA ERS, 2016
Soybean meal	$/kg	0.40	0.39	0.44	0.62	

After total capital investment is calculated, operating costs and total revenues, gross profit, gross margin, net profit, and return on investment (ROI) are calculated following Eq. 3 to Eq. 6. These parameters are critical indices for evaluating the economic feasibility of the whole extruding-expelling process.

$$Gross\ Profit = Total\ Revenue - (Total\ operating\ cost - credits) \qquad Eq.3$$

$$Gross\ Margin\ (\%) = \frac{Gross\ profit}{Revenue} \times 100\% \qquad Eq.4$$

$$Net\ Profit = Gross\ profit - Taxes + Depreciation \qquad Eq.5$$

$$Return\ on\ Investment\ (\%) = \frac{Net\ profit}{Total\ capital\ investment} \times 100\% \qquad Eq.6$$

3. Results and Discussions

3.1 Total Capital Investment

The purchasing cost is the basis for fixed cost estimation. This indicates the required capital which is paid to establish the production stream for producing the products at the begining of the investment. Also, the capital investment will not change with plant service time. In addition to the hardware of the producing stream, WC and SC are necessary to verify the whole process; producing the products that meet required quality. Based on the assumptions of total capital investment, the results of total capital investment for different investment years and handling capacities are shown in Table 3-6.

In different investment years, the total capital investments increased from the 1980s to the 2010s with the growth of the economy and the inflation index. Because of the increasing demands for food applications, the success of RFS (renewable fuel standard program), and the properity of RIN (renewable identification number) markets, many companies began expansion plans in recent years (Biodiesel Magazine, 2015). The capacity increased in scale in six scenarios. Additionally, the largest scale is 2991.93 million kg of annual soybean input; which is also simailar to real oil productivity from the Landus Cooperation soybean expelling plant in Ralston, IA. The relationship between total capital investment and different scales is illustrated in Fig. 3-3.

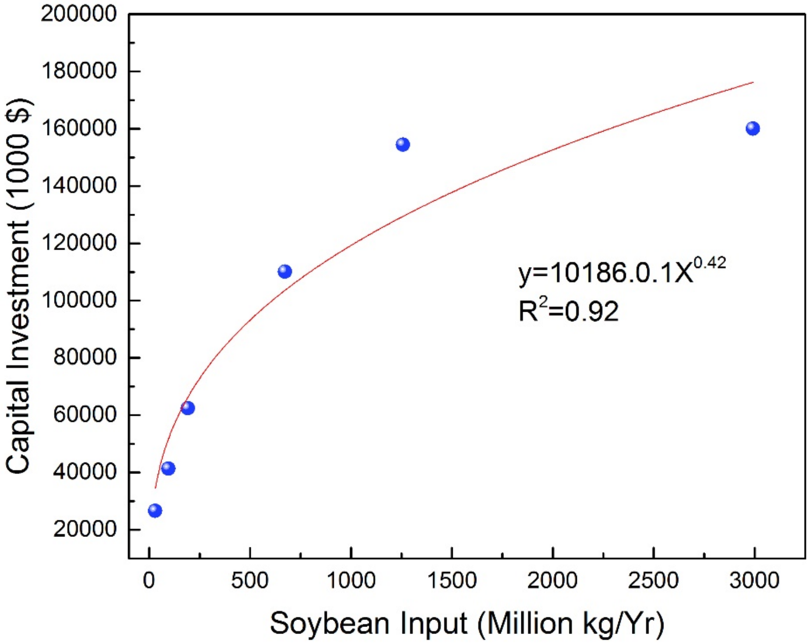


Fig. 3-3 Power relationship between total capital investment and different scales of soybean inputs

A powerful relationship of 0.42 between total capital investment and different annual soybean inputs exsists from the results. This relationship is expressed in Eq. 7, where 'x' is the annual soybean input in million kg and y' is the estimated total capital investment..

$$y = 10186.01X^{0.42} \qquad Eq. 7$$

Table 3-6 Capital investment estimation for extrusion-expelling soybean oil extraction (1000 $ based on 2015 price)

		Scenarios								
Costs	Categories	1980s	1990s	2000s	2010s	30.77M	96.14M	672.28M	1257.53M	2991.93M
Total Plant Direct Cost (TPDC)	Purchase cost (PC)	3,714	5,326	6,896	8,218	3,516	5,406	14,445	20,284	21,322
	Installation	1,506	2,161	2,807	3,342	1,366	2,296	6,044	8,371	8,700
	Process piping	2,525	3,622	4,689	5,588	2,391	3,676	9,823	13,793	14,499
	Instrumentation	996	1,385	1,793	2,137	914	1,406	3,756	5,274	5,544
	Insulation	297	426	552	657	281	433	1,156	1,623	1,706
	Electrical	409	586	759	904	387	595	1,589	2,231	2,345
	Buildings	668	959	1,241	1,479	633	973	2,600	3,651	3,838
	Yard improvement	371	533	690	822	352	541	1,445	2,028	2,132
	Auxiliary facilities	2,043	2,929	3,793	4,520	1,934	2,973	7,945	11,156	11,727
	TPDC	14,499	17,927	23,220	27,669	11,772	18,298	48,801	68,411	70,912
Total Plant Indirect Cost (TPIC)	Engineering	3,750	5,378	6,966	8,301	3,532	5,489	14,640	20,523	21,274
	Construction	4,375	6,274	8,127	9,684	4,120	6,404	17,080	23,944	24,819
	TPIC	8,124	11,652	15,093	17,985	7,652	11,894	31,721	44,467	46,093
Total Plant Cost (TPC)	TPDC+TPIC	20,624	29,579	38,313	45,653	19,423	20,192	80,522	112,877	117,005
Contractor's fee and Contingency (CFC)	Contractor's fee	1,237	1,775	2,299	2,739	1,165	1,812	4,831	6,773	7,020
	Contingency	1,650	2,366	3,065	3,652	1,554	2,415	6,442	9,030	9,360
Direct Fixed Cost (DFC)	TPC+CFC	23,551	33,720	43,676	52,044	22,143	34,419	91,795	128,680	133,385
Working Capital (WC)		3,527	5,508	6,551	7,807	3,321	5,163	13,769	19,302	20,008
Startup Capital (SC)		1,176	1,686	2,184	2,602	1,107	1,721	4,590	6,434	6,669
Total Capital	TPC+CFC+WC+SC	28,213	40,464	52,412	62,453	26,571	41,602	110,154	154,416	160,062

The capacity of 192.28 Million kg of annual soybean input is the basis for estimating different investment years and scales.

3.2 Operating Costs

Operating costs are the basic index for estimating the profit of the whole extruding-expelling process. Operating costs change with the fluctuation of economic conditions, therefore, the percentage changes of materials, utility, labor, and facility related costs in total operating cost are illustrated in Fig. 3-4.

3.2.1 Material Costs

Soybean, water, and phosphoric acid are the sources of material costs, and soybeans take over 98% of the total material cost. In contrast, water and phosphoric acid are only used in the degumming process, and need small amounts for operation. Therefore, they produce less than 1% of the total material costs.

From Fig. 3-4a, the majority of total operating costs increased over 70% from the 1980s to the 2010s. The fluctuation of the cost of materials illustrates the changes of market conditions. From the 1980s to the 2010s, material costs increased about 91%, which caused a portion of material costs to reach about 78% of total costs in the 2010s.

From Fig. 3-4b, the portion of material cost in total operating costs has increased when the plant processing capacity increases in scale. Materials take about 64% of the total operating costs of a facility producing 4.10 million kg of annual oil production; and takes over 85% on the largest scale facilities. This result also indicates the extruding-expelling process is a material intense process because material costs make up the majority of all costs in all scales.

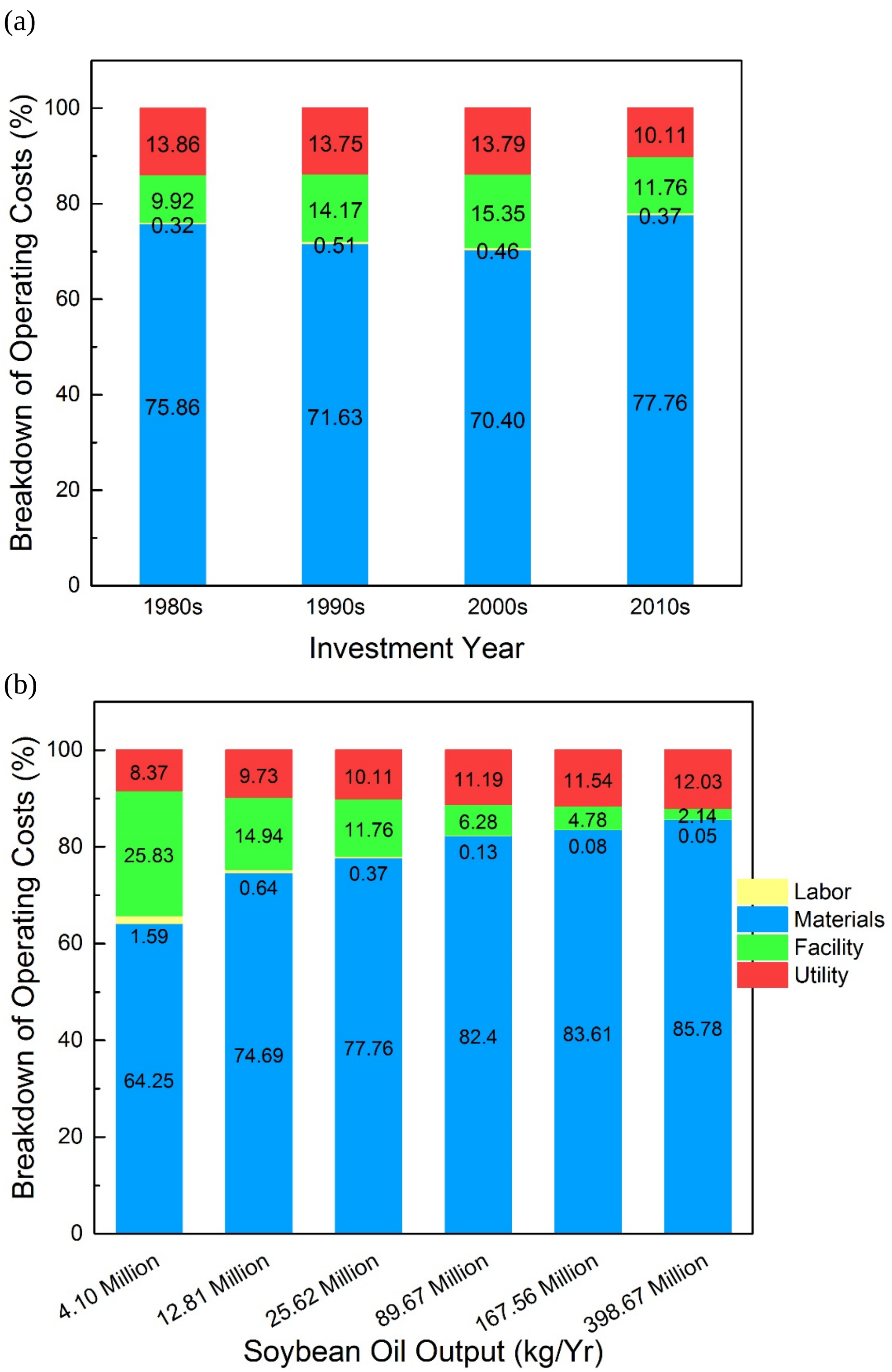


Fig. 3-4 Breakdown of operating costs. (a) 1980-2015 data; (b) Different scales of oil extraction based on 2010s data inputs

3.2.2 Utility Costs

Utility costs includes the electricity, used to operate machines and steam and cooling water, used as heat exchange agents. From Fig. 3-4a, utility costs take over 10% of total operating costs from the 1980s to the 2010s. However, utility cost increased about 40% during that time, which is much less than material costs increasing over 90% from the 1980s to the 2010s. This result causes the portion of utility costs decreased from the 1980s to the 2010s.

According to Fig. 3-4b, when the scale of plant capacity increases, the percentage of utility costs increase. This result also indicates more energy demands are needed to operate large amounts of soybeans. Additionally, the utility cost derived from electricity makes up 90% of all utility costs in all scenarios. This result shows the extruding-expelling process is a high, electricity demand technique in an oil production process.

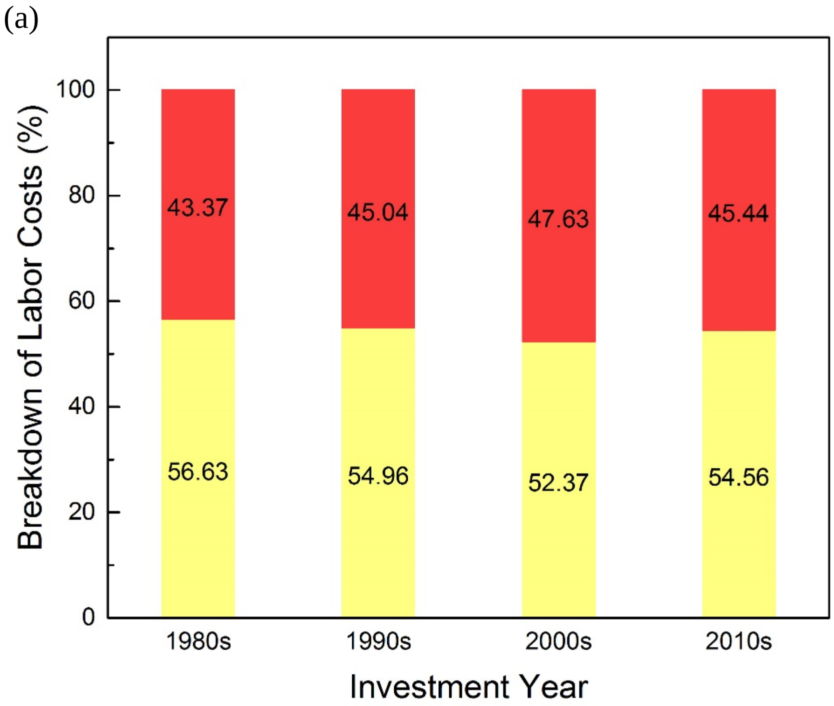
3.2.3 Facility and Labor Related Costs

Facility related costs mainly come from machine maintenance fee. Labor costs include labor dependent and laboratory QA/QC costs.

From Fig. 3-4a, shows facility related costs take up 9-15% of total operating costs. Based on the inflation index, facility related costs increased from the 1980s to the 2000s by about 20%; which means the percentage of facility related costs increased over 14% in the 1990s and 2000s. However, it decreased to about 10% in the 2010s because material cost increased over 55% from the 2000s to recent years. Facility related costs have only increased around 20% from the 2000s.

Based on Fig. 3-4b, the percentages of facility and labor related costs decreased when plant capacity scale increases. This is because more materials and higher utility costs are required in larger scales operations. Though a larger scale facility leads to higher maintenance fees, they still make up a small portion of the total operating cost.

Labor costs take up the smallest percentage of the total operating costs. The breakdown of labor costs is shown in Fig. 3-5. According to Fig. 3-5a, results demonstrate the wage of an extraction worker has increased more than an agricultural machine worker for the last three decades. For different plant capacities (Fig. 3-5b), the cost of an agricultural machine worker increases when the capacity increases in scale. This also indicates more agricultural machine workers are needed for dealing with the crop-handling process. These results indicate the extruding-expelling process is an agricultural machine intense technique, and shows the characteristics of the mechanical process.



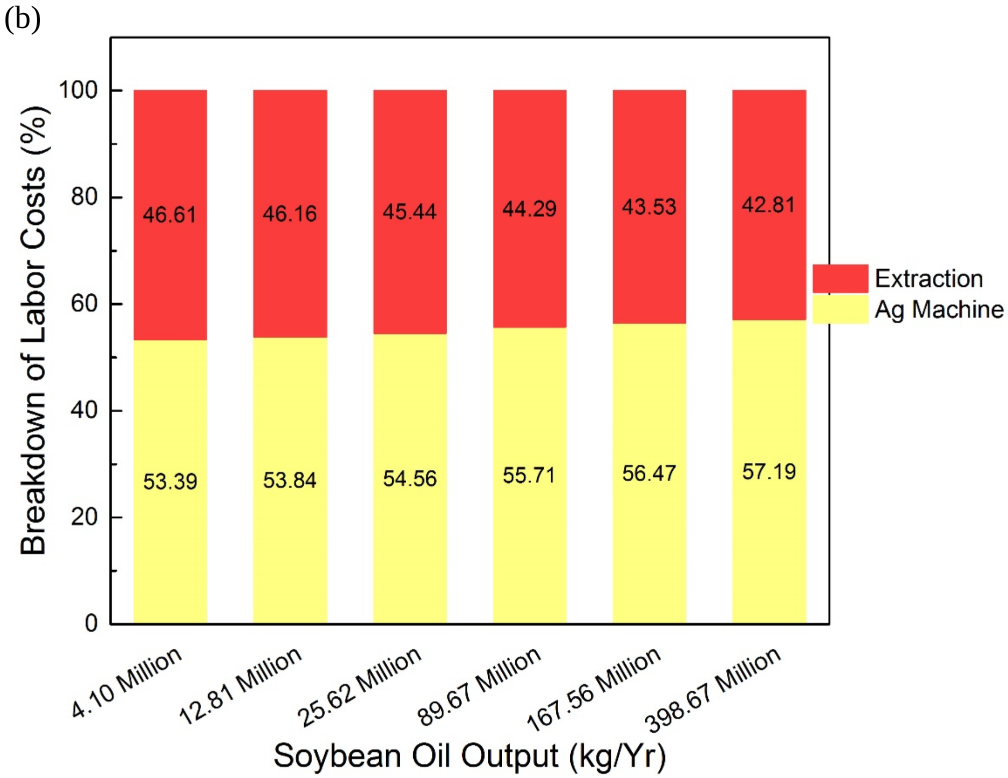


Fig. 3-5 Breakdown of labor costs. (a) 1980-2015 data; (b) Different scales of oil production based on 2010s data inputs

3.2.4 Unit Producing Cost

The unit producing cost is calculated by dividing total annual operating cost with annual soybean oil productivity. Based on the referred scale, between the 1980s to the 2010s the unit producing cost of soybean oil production has increased from $2.26 to $4.23 per kg because of the change and increasing value of economic and market conditions.

The effects of different plant capacities are shown in Fig. 3-6. From these results, the unit producing cost has decreased from $5.12 to $3.80 per kg of soybean oil when the facility capacity is increased in scale. Additionally observed is a power relationship of -0.07 between unit producing cost and soybean oil output.

The unit operating cost is also calculated by dividing total annual operating cost with annual soybean input. A similar trend was observed, with unit producing cost (Fig. 3-7) and a -0.07 power relationship between unit operating cost and different plant capacity. The unit operating cost decreased from \$0.68 to \$0.51 per kg of annual soybean input when the capacity increases in scales..

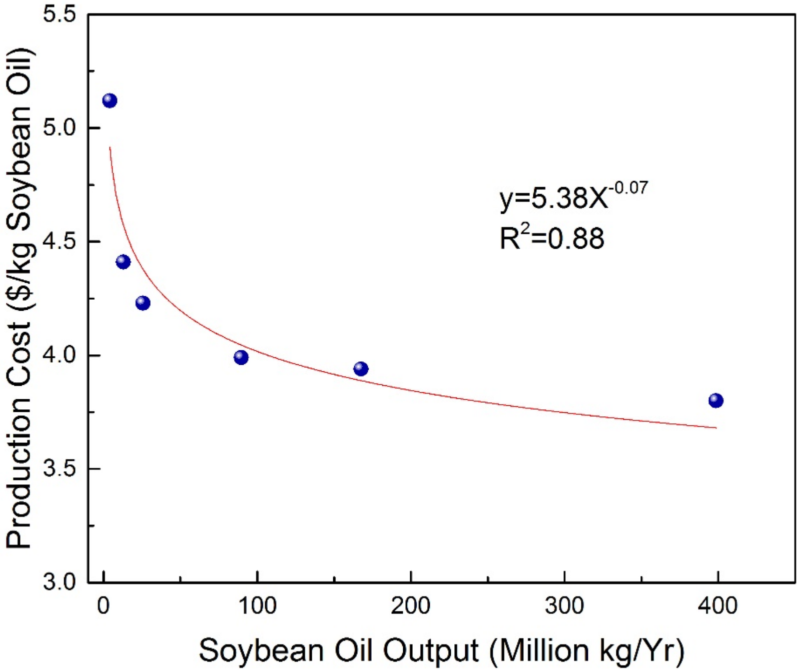


Fig. 3-6 Power relationship between net unit producing cost and different scales of soybean oil production

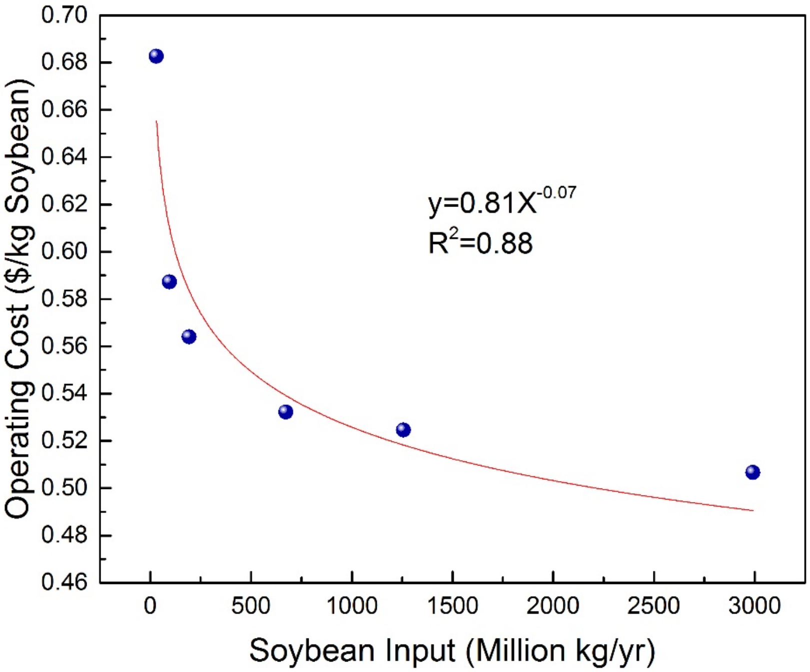


Fig. 3-7 Power relationship between net unit operating cost and different scales of soybean inputs

3.3 Revenues and Profits

Degumming crude soybean oil and soybean meal are products of the extruding-expelling process. The annual revenues, gross profit and net profit are illustrated in Fig. 3-8.

Based on the productivities of soybean oil and soybean meal, revenues from soybean oil and meal are 23% and 77% respectively. Though the oil expelling process is used to produce oil, the meal might be the driving force for the whole producing stream.

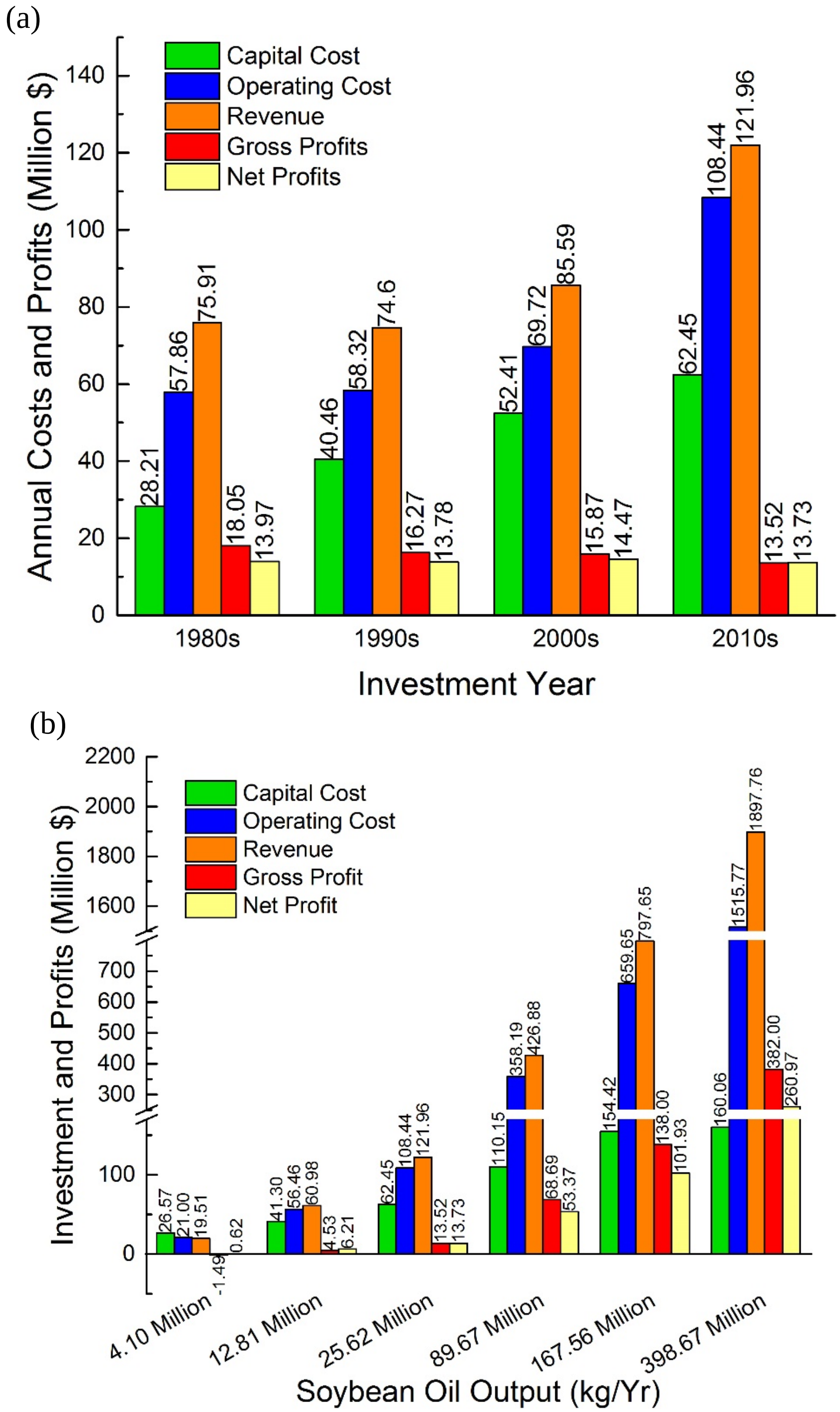


Fig. 3-8 Capital investment, gross and net profits of soybean oil extruding-expelling process. (a) 1980-2015 data; (b) Different scales of oil production

From Fig. 3-8a, the increasing economic and markets can be also observed. The extruding-expelling process has positive gross and net profits, indicating this process could be profitable. The effect of different plant capacities (Fig. 3-8b) shows, all parameters increase when the capacity is scaled up. A plant producing 4.10 million kg of soybean oil annually, with a negative gross profit, can have a positive net profit when depreciation is considered. Additionally, a positive gross profit can be obtained when the capacity is larger than 12.81 million kg of annual soybean oil output, which indicates the break-even point of the extrusion-expelling process is between the capacity of 30.77 and 96.14 million annual soybean input.

According to the ROI, payback time can be calculated by following the Eq. 8. The economic feasibility of the process is determined by gross margin and payback time. The results are shown in Table 3-7. From gross margin results, positive values are observed when the capacity is larger than 12.81 million kg of annual soybean oil output. Though the capacity of the 12.81 million kg of annual soybean output has a positive ROI, which shows there is the potential for the process to earn profit back; however, the payback time is longer than fifteen years, which is set as the service time of this project. Therefore, this scale cannot be regarded as a profitable and economically feasible process. Conclusively, a process with a positive gross margin and a payback time shorter than service time is considered a profitable process. Thus, when the capacity of the extrusion-expelling process has a capacity larger than 30.77 million kg of annual soybean input, it can be a profitable and economically feasible process.

$$\text{Payback Time} = \frac{100}{\text{ROI}} \qquad \text{Eq. 7}$$

Table 3-7 Gross margin, ROI and payback time of different scales of soybean oil production

	Soybean Annual Output (million kg)					
	4.10	12.81	25.62	89.67	167.56	398.67
Gross Margin (%)	-7.62	7.42	11.09	16.09	17.30	20.13
ROI (%)	2.32	15.04	21.99	48.45	66.01	163.04
Payback Time (yr)	43.14	6.65	4.55	2.06	1.52	0.61

4 Conclusions

Mechanical expelling is the typical technique used to extract oil from crops by using heat and pressure. The extruding-expelling process simplifies and increases the efficiency of the whole process. Not only does it lower the total capital investment, but also saves operating cost compared to the typical expelling process. Results show the extruding-expelling process is an economically feasible technique when the plant capacity is larger than 30.77 million kg of annual soybean input. Moreover, soybean meal might be the driving force of the whole process because it provides over 70% of the total revenue. Additionally, higher values of expelled meal are the main reasons of higher revenue due to its higher oil content; which results in higher energy content. This is also the reason why the mechanical expelling process still exists for specific applications. The high electricity intense process demonstrates the properties of the mechanical expelling process.

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CHAPTER 4

TECHNO-ECONOMIC ANALYSIS OF SOYBEAN OIL HEXANE EXTRACTION PROCESS

Modified from a paper to be submitted to *Industrial Crops and Products*

Abstract

Hexane extraction is the most common method used in the industry to produce soybean oil due to its high oil recovery and lower producing cost. With the demands of soybean oil increasing, either in food or industrial applications, expansion plans are being considered by many companies to increase production capacity. Techno-economic analysis (TEA) is performed to evaluate the economic feasibility of soybean oil production by hexane extraction based on historical scenarios from 1980 to 2015. Capital investment, operating costs, revenues, and profits are main parameters to consider when estimating profits, gross margin, return on investment (ROI), and payback time and are the indices used to evaluate the profitability of the process. As the plant capacity increases in scale to over 34.64 million kg of annual soybean oil production, the break-even is met and the production stream is able to earn profits. Comparing to the extruding-expelling process, higher capital investments are needed for the hexane extraction process at the similar operation capacities. In revenues, soybean meal provides about 60% of total revenues. Thus, soybean meal might be the driving force for solvent extraction process as well.

Keywords: Hexane extraction, Soybean oil, Techno-economic analysis, Profits, Soybean meal

1. Introduction

Soybeans, the main oil crop in the world, make up 56% of world oil seed production; and the U.S. is the major producer with 33% (SoyStats, 2016[a]). Soybean oil is the major source of American vegetable oil consumption, and takes around 57% of all vegetable oil resources (SoyStats, 2016[b]). Typically, vegetable oil is obtained using the mechanical process, expelling or hot pressing, or a chemical process such as solvent extraction. Organic solvent extraction is the most common and efficient method for oil production; and can be applied to seeds with oil content lower than 20% and higher oil content (Anderson, 2016).

Hexane extraction is used in the vegetable oil production industry because of its low cost and high solubility (Hammond et al., 2005, Sawada et al., 2014). However, pure *n*-hexane is not used for extraction, instead a mix of isomers with similar properties is used. It is called extraction grade hexane or commercial hexane, with *n*-hexane take about 50%-90% in extraction grade hexane by volume (Woerfel, 1995). Extraction grade hexane has lower boiling and melting points (-154^{o}C and 56-60^{o}C) than *n*-hexane; moreover, it has a higher ignition point 264^{o}C compared to 225 ^{o}C of *n*-hexane (NFPA, 2009). In addition to these properties, its similar density, molecular weight of *n*-hexane, and the presence of various isomers give extraction grade hexane a greater ability to extract oil from oilseeds (Anderson, 2011).

In hexane extraction, the process includes crop cleaning, cracking, dehulling, conditioning, flaking, extracting, solvent recovery, and desolvenization. For soybean oil production, soybean hulls recovered from the dehulling process, and soybean meal generated after desolvenization are co-products sold as animal feeds. For improving yield and profits of the solvent extraction process, plants work to increase energy efficiency, cost reduction, and quality control of products as the solvent extraction process initially expanded in industrial application in the 1930s (Langhurst, 1951).

Recently, soybean production and its refinery products such as soybean oil, and soybean meal, significantly increased due to their nutritional values and wide utilizations in the food industry and non-food applications (Do et al.,2014). For conventional food and animal feed usage, soybeans are a good resource of oil, protein, fiber (Bader et al., 1999), and minerals and vitamins (Corley et al., 1999). In the U.S., the area for soybean plantation increased around 30% from the 1980's to 2015 (SoyStats, 2016[c]) because the need for soybean products increased with population growth. Soybean meal, one resource for animal feeds due to its high protein and fiber content, increased over 45% from the 1980s; with annual production in the U.S. reaching 44 million short ton in 2015 (SoyStats, 2016[d]). In other applications, soybeans are suppliers of industrial raw materials and used in the production of many products like plastics, detergents, and lubricants. (Perez and Nolasco, 2010).

To obtain high oil yield and good quality, a well-designed process is necessary. The physical properties of grain and diffusivity are two major issues in the solvent extraction process (Perez et al., 2011). Though a proper hexane extraction approach could minimize these problems, it still has some defects such as non-renewable fossil origin, leading to environmental pollution and public health issues (Rosenthal et al., 1996, Oliveira et al.,2013, Tabtabaei & Diosady, 2013). Many researchers have been using different solvents (Bhagya & Srinivas, 1992, Myint et al., 1996, Do et al., 2014, Sawada et al., 2014) and different techniques (Domínguez et al., 1995, Ribeiro et al.,2006, Eikani et al., 2012) to improve oil yield and reduce solvent consumption, which causing environmental impact and safety issues.

The first mathematic model to predict the oil extraction yield based on experimental data was established by Karnofsky in 1949; and mainly focused on soybean, cottonseed and peanuts. For vegetable oil production, other than techniques used to improve oil yield and quality, economic feasibility is another critical factor. Oil extraction is the first step of oil applications. Some studies on the economics of vegetable oil utilizations, include the oil extraction step in their economic analysis models. Nelson et al. (1994) conducted economic analysis of 100,000 ton/year biodiesel with beef tallow and methanol by acid catalysis. A similar study was performed by Noordam and Withers (1996) using canola seeds as the material for biodiesel production. Haas et al. (2006) performed the operation cost estimation of soybean-based biodiesel production. Additionally, there are still different economic modeling analyses used for biodiesel production with different software (Bender, 1999, Zhang et al., 2003, Marchetti et al., 2008, Mlay et al., 2014). However, few studies about economic feasibility and cost effects focusing on soybean oil extraction process have been completed.

According to prior studies on oil conversion, previous models are regarded as a proper reference for economic analysis of the hexane extraction process. The targets of pilot and commercial scale productions try to lower the capital investment and operating cost while increasing the yield and quality to earn more profits. However, each process unit could affect not only cost, but also yield and final profits. The soybean oil and meal co-products are another critical factor that increase total profits. The high protein and fiber contents of soybean meal and soybean hulls are also valuable merchandise for other industries and markets.

This study focuses on the typical hexane extraction process for degummed crude soybean oil production. The goal of this study is to build up an economic model of hexane oil extraction in several industrial scales to estimate production cost, economic feasibility, and the effects on profits from operating costs and revenues. This model can be used not only in the vegetable oil industry, but expanded to further bio-refinery applications and other relative applications.

2. Materials and Methods

2.1 Hexane Extraction Process

Crop preparation (handling), solvent extraction, degumming, desolvenization and meal processing are main processes of the soybean oil hexane extraction process (Fig. 4-1). Crop preparation includes oil seed cleaning, cracking, dehulling, conditioning, and flaking. The purpose of crop handing and preparation is to remove foreign impurities, separate soybean hulls from seeds, and increase the accessibility for oil release. In the conditioning process, heat makes the soybean meal plastic and breaks down the linkage between proteins and oil bodies. The following flaking process increases surface area and makes soybean flakes more porous; which improve the efficiency of further oil recovery.

In the extraction process, solubility of oil in organic solvent is used as the principle source of solvent extraction, and continuous countercurrent percolation is applied to reduce hexane usage. Also, hexane is recycled and reused to reduce material cost and minimize environmental and safety issues. Heat evaporates hexane from the oil and solvent solution. The hexane vapor is condensed by cooling water to be recycled and reused. After extraction, a water degumming process removes most parts of the phospholipids, which is water soluble, and can be separated by centrifugation. The amount of water used in the degumming process corresponds to phospholipid content in soybean oil with a 1:1 ratio by weight (Dijkstra, 2016). Once the phospholipid is removed, soybean oil is sold as degummed crude soybean oil in commodity.

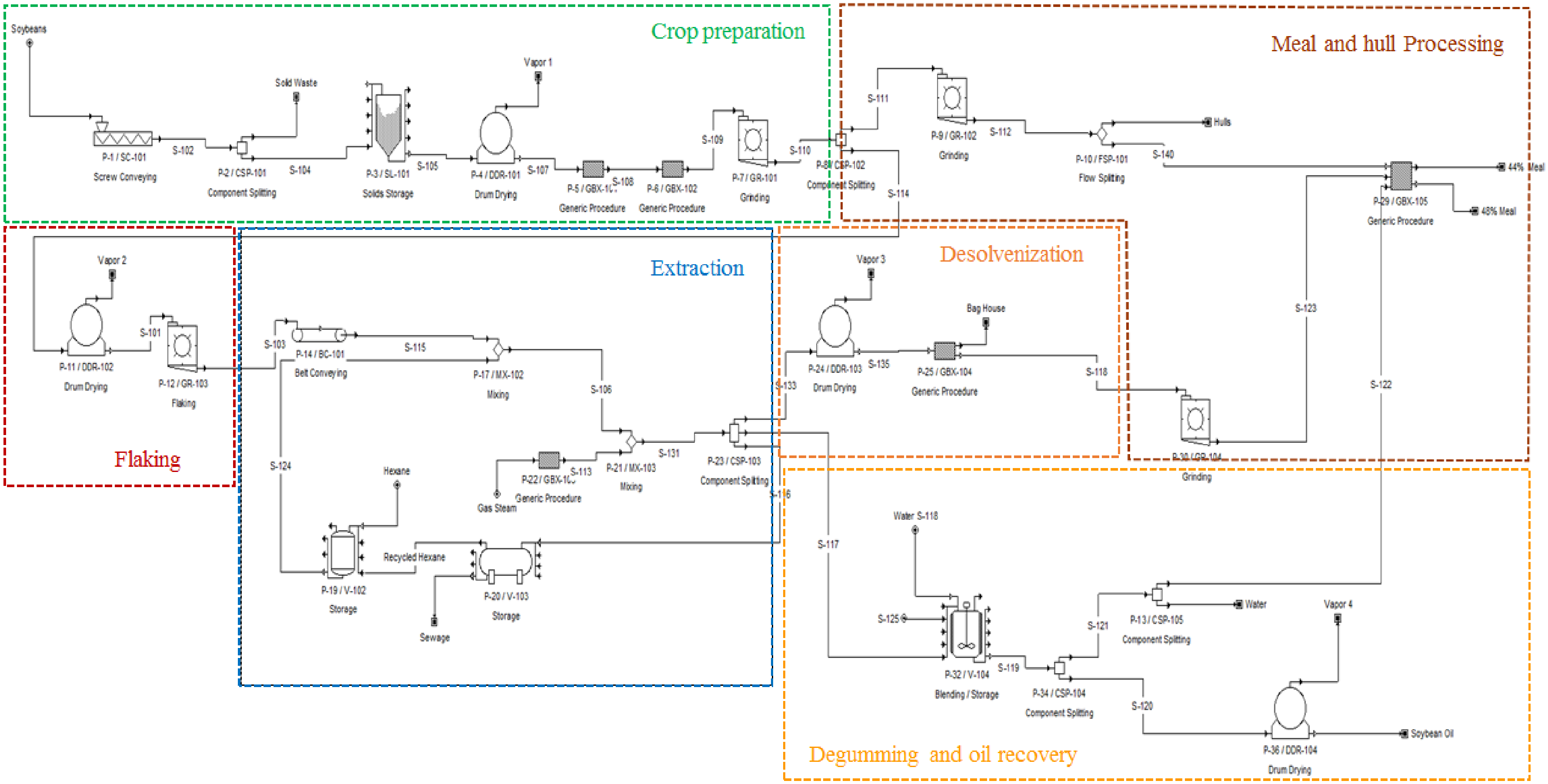

Fig. 4-1 Soybean oil hexane extraction TEA model

The desolvenization process follows the extraction process, using steam to evaporate hexane remaining in soybean meal. Typically, desolvenization is conducted by a toaster, and steam flow runs countercurrent to meal flow to improve efficiency. Hexane vapor generated from desolvenization is also collected to prevent potential safety risks. However, the soybean meal and hulls produced and collected from oil extraction are regarded as co-products; which are sold as materials for animal feed applications.

2.2 Computer Modeling

The economic model of soybean oil hexane extraction was performed by SuperPro Designer v9.0 (Intelligen, Inc., Scotch Plains, NJ). The simulation followed mass balance. Additionally, equipment, facility and economic parameters of production stream were evaluated in the model (Ngo et al., 2014).

According to the TEA model of soybean based biodiesel production established by Hass et al., (2005), 192.28 million kg/year of soybean input was set as the referred scenario and scale for time-piece and different capacities studies. Additionally, this capacity is a common scale used in the industry (U.S. EPA, 2001). Historical economic parameters (1980s~2010s) and different oil production capacities (4.04, 12.12, 34.64, 86.61, 173.22 and 415.73 million kg of annual soybean oil production which correspond to 22.43, 67.30, 192.28, 480.71, 961.42, and 2307.40 million kg of annual soybean handling) were analyzed in this study. The model was built for 15 years of plant life time, 30 months of construction, four months of startup time, 35% income tax, and a ten year depreciation period with 5% salvage value of directed costs (Haas et al., 2006).

2.3 Assumption and Data Collection

2.3.1 Fixed Costs

Fixed costs mainly come from facility and hardware costs. They are divided into total plant direct cost (TPDC), total plant indirect cost (TPIC), and contractor fees and contingency (CFC). TPDC includes items like facility installation, processing pipe connections, and instrumentation; and TPIC includes engineering and construction fees. Total plant cost (TPC) is estimated by total TPDC and TPIC. Additionally, the summation of TPC, CFC, startup costs and working capital is total capital investment for the whole producing line. The fee to purchase the facility is used as the base to estimate fixed costs and is calculated using different multipliers (Table 4-1) (Heinzle et al., 2006).

Table 4-1 Multiplier for directed cost and total capital investment estimation

Costs	Categories	Multipliers*
Total Plant Direct Cost (TPDC)	Purchase cost (PC)	
	Installation	0.47×PC
	Process piping	0.68×PC
	Instrumentation	0.26×PC
	Insulation	0.08×PC
	Electrical	0.11×PC
	Buildings	0.18×PC
	Yard improvement	0.10×PC
	Auxiliary facilities	0.55×PC
	TPDC	2.43×PC
Total Plant Indirect Cost (TPIC)	Engineering	0.30×TPDC
	Construction	0.35×TPDC
	TPIC	
Total Plant Cost (TPC)	TPDC+TPIC	
Contractor's fee and Contingency (CFC)	Contractor's fee	0.06×TPC
	Contingency	0.08×DFC
Direct Fixed Cost (DFC)	TPC+CFC	
Working Capital (WC)		0.15×DFC
Startup Capital (SC)		0.05×DFC
Total Capital	TPC+CFC+WC+SC	

The purchasing cost (PC) of each machine is collected from Haas' research (2006), the SuperPro designer v9.0 database, and the inventory record of Iowa State University Center for Crops Utilization Research (CCUR) pilot. Inflation index (BLS^a, 2016) is used to estimate machine purchase price from 1980 to 2015 following Eq. 1; where, P_c is the inflation-adjusted price of equipment in a current year, P_p indicates the cost of equipment in the previous year, and I_c and I_p are inflation index factors of current and previous year respectively. Additionally, the six-tenths rule (n=0.6) is used to estimate machine PC for different production capacities (Ulrich, 1984; Peters et al., 2011) following Eq. 2. In Eq. 2, PC_p and PC_c are facility purchasing costs of predicted and base scales and q_p and q_c indicate the capacity of the facilicty of predicted and base scales respectively. However, the power (n) varies based on different types of machine, and is listed in Table 4-2.

$$P_c = P_p \times \left(\frac{I_c}{I_p}\right) \qquad Eq. 1$$

$$PC_p = PC_c \times (\frac{q_p}{q_c})^n \qquad Eq. 2$$

Table 4-2 Facility prices and power (n) used for PC estimation of different capacities (2015 price)

	Power (n)	PC of referred scale (1000$)
Conveyor*	0.6	9
Storage bin*	0.6	1400
Drum dryer+	0.4	91
Grinder+	0.6	113
Aspirator●	0.6	13
Conditioner+	0.4	91
Flaking miller●	0.6	822
Extractor and toaster+	0.6	2150
Degumming tank●	0.49	67
Centrifuge●	0.49	589
Dryer for oil recovery+	0.4	28
Hexane receiving tank*	0.54	248
Hexane storage tank*	0.49	125
Meal grinder+	0.6	42
Hull grinder+	0.6	22
Meal processer+	0.49	2590

Date adjusted according to SuperPro Designer database (*), Haas' research (+) and Iowa State University CCUR pilot inventory record (●).

2.3.2 Operating Costs

Material, labor, facility maintenance, and utility costs are the main sources of operating costs. Soybeans, hexane, and water used in the extraction and degumming processes are some material costs. Electricity is the main energy used to operate a facility; while steam and natural gas are used as heat transfer agents in the process. Labor costs are divided into agricultural machine operators, extraction workers, and hazardous material workers. Operating costs from 1980 to 2015 are presented as average prices for each 10-year period and are listed in Table 4-3.

Table 4-3 Operating costs inputs

		Unit	1980s	1990s	2000s	2010s	Citation
Materials	Soybean	$/kg	0.228	0.217	0.255	0.438	USDA ERS, 2016
	Hexane	$/kg	0.89	0.89	0.89	0.89	SuperPro Database
	Water	$/L	0.001	0.001	0.001	0.001	Ames, 2016
Utility	Electricity	$/kwh	0.047	0.047	0.057	0.066	EIA, 2016
	Steam	$/MT	12	12	12	12	SuperPro Database
Labor	Ag. machine operator	$/hr	6.36	8.77	10.19	13.12	BLS[b], 2016
	Extraction worker	$/hr	9.30	13.72	17.69	20.86	
	Hazardous material worker	$/hr	9.13	13.26	17.78	20.11	

To estimate labor costs, agricultural machine workers are assigned to cope with crop preparation and co-product handling; extractor workers handle extraction and degumming processes, and hexane recycling and desolvenization are operated by hazardous material workers. The labor requirements for each machine are set between 0.1-1 (workers/unit/shift) and a shift is typically 8 hours for basis scale, which are listed in Table 4-4. However, the relationship between labor requirements and the capacity of production is not a linear relationship. A 0.2-0.25 power of the capacity ratio is typically applied in plant scale-up (Peters et al., 2011). In this study, a 0.25 power is used for optimal estimation. Additionally, the laboratory quality control and assurance costs are considered and estimated by 15% of total labor cost (TLC) (Heinzle et al., 2006). Additionally, the energy consumption inputs are listed in Appendix Table A-2.

Table 4 Labor requirement for each operating facility (workers/unit/shift)

	Soybean Oil Annual Input (million kg)					
	22.43	67.30	192.28	480.71	961.42	2307.40
Conveyor	0.21	0.22	0.25	0.30	0.30	0.33
Storage bin	0.08	0.08	0.10	0.11	0.13	0.16
Drum dryer	0.65	0.76	1	1.16	1.38	1.70
Grinder	0.85	1	1	1.2	1.42	1.78
Aspirator	0.20	0.30	0.30	0.35	0.40	0.47
Conditioner	0.65	0.76	1	1.26	1.50	1.85
Flaking miller	0.72	0.76	1	1.20	1.40	1.73
Extractor and toaster	2.39	2.52	3	3	3.17	3.95
Degumming tank	0.60	0.78	1	1.45	1.78	1.88
Centrifuge	0.75	0.75	1	1.20	1.40	1.78
Dryer for oil recovery	1	1	1	1	1	1
Hexane receiving tank	0.67	0.74	1	1.20	1.40	1.76
Hexane storage tank	0.67	0.74	1	1.20	1.40	1.76
Meal grinder	0.80	0.84	1	1.32	1.50	1.82
Hull grinder	1	1	1	1.19	1.41	1.72
Meal processer	0.20	0.22	0.35	0.35	0.40	0.47

Labor requirements are adjusted according to different production scales of each operating facility. These inputs are collected based on Ulrich’s (1984) and Peters’ (2011) studies.

2.3.3 Revenues

Soybean oil, meal, and hull are products of the whole producing line. The selling prices from 1980 to 2015 are presented as average prices for each 10-year period and listed in Table 4-5. Operating costs and total capital investment, gross profit, gross margin, net profit and return on investment (ROI) are calculated following Equations 3 to 6.

Table 4-5 Selling prices of products from soybean oil hexane extraction process

	Unit	1980s	1990s	2000s	2010s	Citation
Soybean oil	\$/kg	0.49	0.50	0.62	0.94	USDA ERS, 2016
Soybean meal	\$/kg	0.22	0.22	0.26	0.45	USDA ERS, 2016
Soybean hull	\$/kg	0.06	0.06	0.12	0.21	Feedstuffs Magazine, 1980-2015

$$Gross\ Profit = Total\ Revenue - (Total\ operating\ cost - credits) \qquad Eq.3$$

$$Gross\ Margin\ (\%) = \frac{Gross\ profit}{Revenue} \times 100\% \qquad Eq.4$$

$$Net\ Profit = Gross\ profit - Taxes + Depreciation \qquad Eq.5$$

$$Return\ on\ Investment\ (\%) = \frac{Net\ profit}{Total\ capital\ investment} \times 100\% \qquad Eq.6$$

3. Results and Discussions

3.1 Total Capital Investment

Facilities machines for processing are a major part of the total investment. These costs are necessary before the process is operational, and are defined as fixed cost. Working capital and startup costs are also considered in fixed cost, which is defined as additional costs used for validation and start-up of a facility before a plant starts producing products. This additional cost includes installation and operational and process qualifications; which assures the plant meets required quality and safety standards (Heinzle et al., 2006). The results of the total investment are shown in Table 4-6.

According to the estimation of fixed cost, investment increased from 1980s to 2010s with growth of the economy, and is observed in the inflation index as well. Due to many expansion plans implemented by companies since 2010 (Biodiesel Magazine, 2015), the 2010 model of 192.28 million kg of annual soybean annual input (Haas et al., 2006) is the basis for estimation of different scales. The result of relationships between capital investment and different scales of annual soybean input is illustrated in Fig. 4-2.

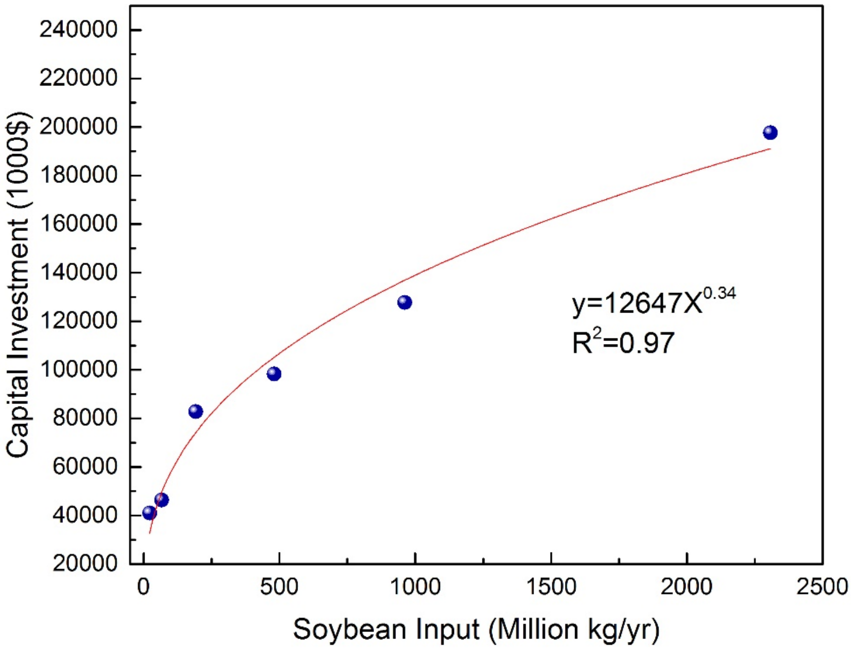

Fig. 4-2 Power relationship between total capital investment and different scales of soybean oil extraction

Results show there is a power relationship of 0.34 between capital investment and different scales of soybean annual input. However, the total capital investments of hexane extraction are higher about 8%-110% than the extruding-expelling process depending on different operating scales. Equation 7 is used to estimate the potential capital investment based on ratios used for facilities scaling up; where, 'x' indicates the ratio of scaling up based on 192.28 million kg of soybean input, and 'y' is the estimated capital investment in thousands of dollars.

$$y = 77.05X^{0.34} \qquad Eq.7$$

Table 4-6 Capital investment estimation for hexane soybean oil extraction (1000 $ based on 2015 price)

		Scenarios								
Costs	Categories	1980s	1990s	2000s	2010s	22.43M	67.30M	480.71M	961.42M	2307.4M
Total Plant Direct Cost (TPDC)	Purchase cost (PC)	5,464	7,830	10,080	10,886	5,419	6,107	12,961	16,869	26,139
	Installation	2,255	3,231	4,164	4,443	2,126	2,456	5,159	6,646	10,179
	Process piping	3,715	5,324	6,854	7,403	3,685	4,153	8,814	11,471	17,774
	Instrumentation	1,421	2,036	2,621	2,830	1,409	1,588	3,370	4,386	6,796
	Insulation	437	626	806	871	434	489	1,037	1,350	2,091
	Electrical	601	861	1,109	1,198	596	672	1,426	1,856	2,875
	Buildings	983	1,409	1,814	1,960	975	1,099	2,333	3,036	4,705
	Yard improvement	546	783	1,008	1,089	542	611	1,296	1,687	2,614
	Auxiliary facilities	3,005	4,306	5,544	5,988	2,980	3,359	7,129	9,278	14,376
	TPDC	18,428	26,407	34,000	36,667	18,166	20,534	43,524	56,578	87,549
Total Plant Indirect Cost (TPIC)	Engineering	5,528	7,922	10,200	11,000	5,450	6,160	13,057	16,973	26,265
	Construction	6,450	9,243	11,900	12,833	6,358	7,187	15,233	19,802	30,642
	TPIC	11,978	17,165	22,100	23,833	11,808	13,347	28,291	36,775	56,907
Total Plant Cost (TPC)	TPDC+TPIC	30,406	43,572	56,100	60,500	29,974	33,881	71,814	93,353	144,457
Contractor’s fee and Contingency (CFC)	Contractor’s fee	1,824	2,614	3,366	3,630	1,798	2,033	4,309	5,601	8,667
	Contingency	2,433	3,486	4,488	4,840	2,398	2,710	5,745	7,468	11,557
Direct Fixed Cost (DFC)	TPC+CFC	4,257	6,100	7,854	8,470	4,196	4,743	10,054	13,069	20,224
Working Capital (WC)		5199	7,451	9,593	10,346	5,126	5,794	12,280	15,963	24,702
Startup Capital (SC)		1,733	2,484	3,198	3,449	1,708	1,931	4,093	5,321	8,234
Total Capital	TPC+CFC+WC+SC	41,596	59,607	76,745	82,764	41,004	46,349	98,242	127,707	197,617

The capacity of 192.28 Million kg of annual soybean oil input from 1980s to 2010s is the basis for estimation of different scales.

3.2 Operating Costs

Operating costs are a critical index for estimating profits of the producing stream based on Equation 3. Unlike fixed cost, operating costs change annually depending on economic and market conditions. Materials, utility, labor, and facility related costs are the main sources of operating costs (Fig. 4-3).

Fig. 4-3a shows material cost make up the majority of operating costs for the reference scale of a facility producing 192.28 million kg of soybean annual input. Results also indicate a change of operating costs from fluctuating economic and market conditions, especially for material and utility costs. Additionally, the facility related cost is another critical source of operating costs, and is mainly from facility maintenance fees. Therefore, results show hexane extraction is a material and facility intense process, especially for plants with the handling scale of 192.28 million kg soybean annual input.

3.2.1 Material Costs

Soybean, hexane and water are the sources of materials costs; with soybeans taking up 99% of total material cost. Because hexane is recyclable and runs counter-current with the percolation process applied in extraction, the cost of hexane is remarkably low.

Fig. 4-3b shows a portion of materials in operating costs increases when the capacity of the facility increases. Material cost takes up about 44% of total operating costs in a facility producing 4 million kg of soybean oil and increases to over 90% of total operating costs in 173.22 and 415.73 million kg of soybean oil production facilities. Therefore, the soybean price is concluded as a critical factor for the hexane extraction process.

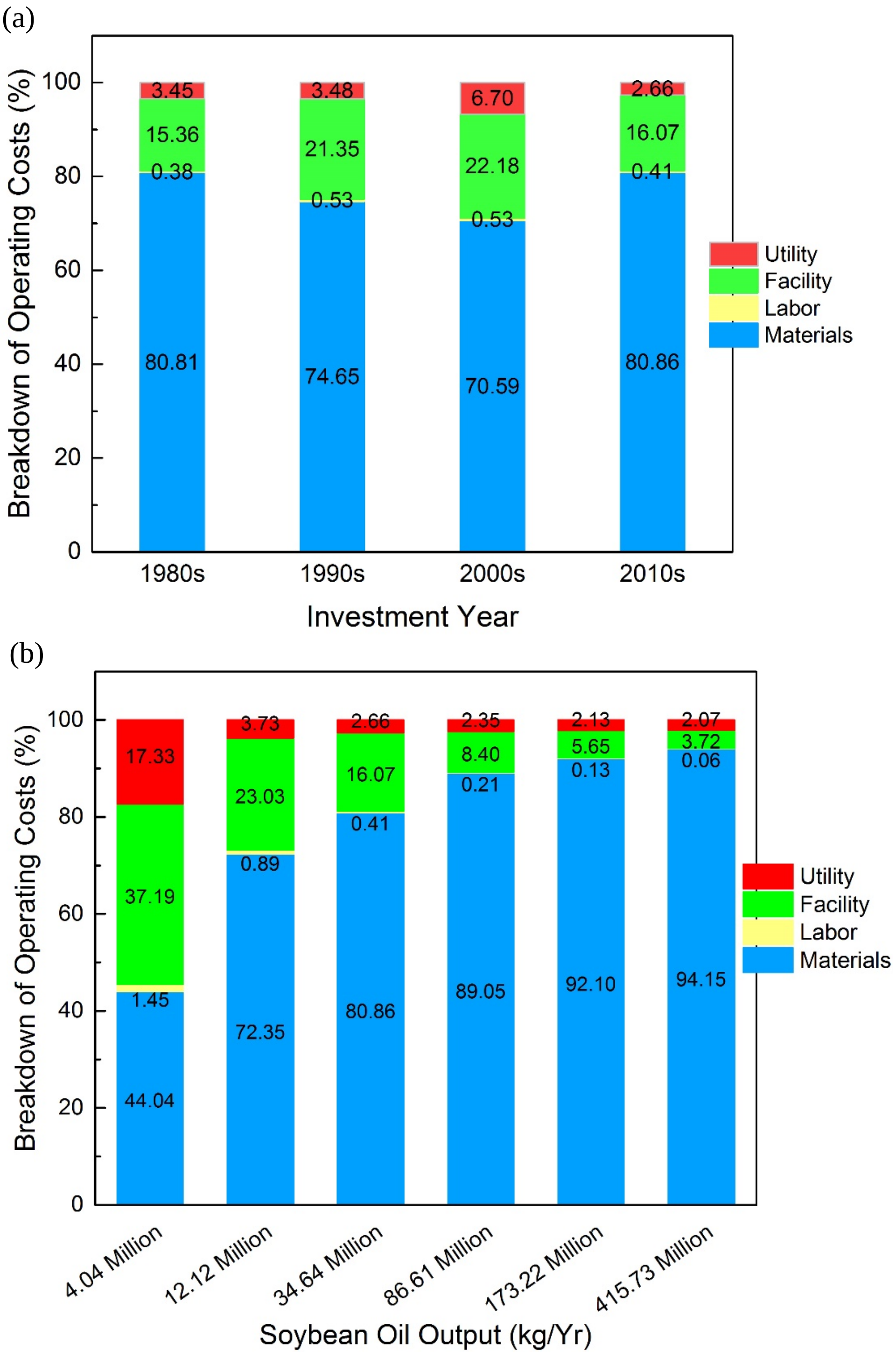

Fig. 4-3 Breakdown of operating costs. (a) 1980-2015 data; (b) Different scales of soybean oil extraction

3.2.2 Utility Costs

Electricity and steam are main energy inputs for the extraction process. Electricity powers the facilities and steam heats the resources for the process. The breakdown of utility costs is shown in Fig. 4-4. After the year 2000, steam prices increased remarkably. Therefore, the obvious increment increases of electricity costs can be observed in the 2010s.

According to Fig. 4-3b, the percentage of utility costs decreases when the capacity increases. Producing 4 million kg of soybean oil means utility costs take up about 17% of total operating costs; but only take up about 2% in larger scales. Though more energy inputs and utility fees are required for larger scale operations of soybean oil production, material costs play a critical role in the whole process, especially for soybean cost. Material costs exceed other operating costs resulting in a lower percentage of utility costs in all operating costs.

As shown in Figure 4-4b, there is an obvious trend of increasing steam cost. More energy inputs are needed in larger scales of production for soybean drying, conditioning process, and desolvenization process. The amounts of steam required increases from 4568 MT in the 22.43 million kg of annual soybean input to over 35000 MT in the largest scale which results in an over six times increments of steam cost.

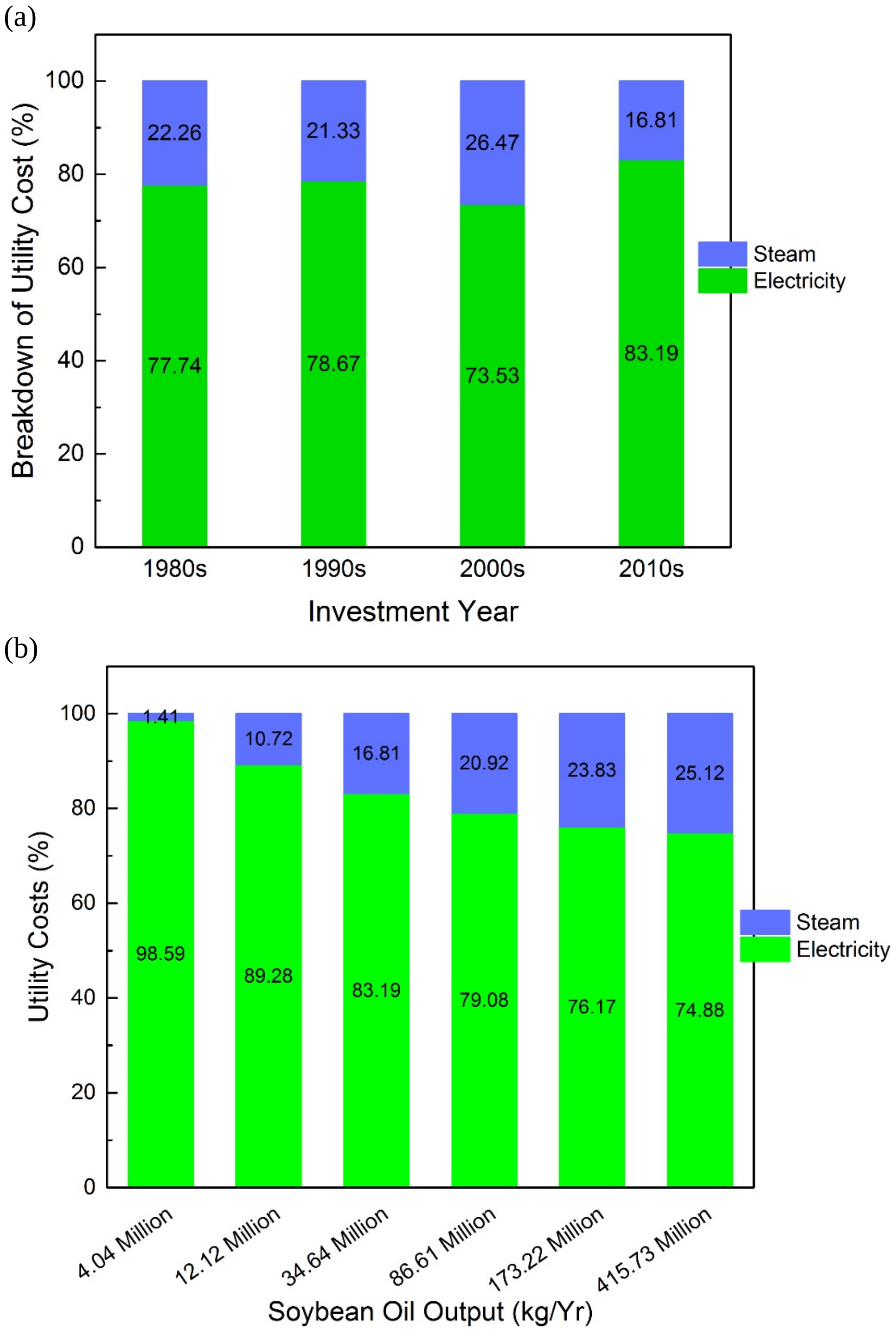

Fig. 4-4 Breakdown of utility costs. (a) 1980-2015 data; (b) Different scales of soybean oil extraction

3.2.3 Facility and Labor Related Costs

Facility related cost is mainly from routine maintenance and repair fees, which is estimated as 7% of total direct fixed cost (Heinzle et al., 2006, Peters et al., 2011). Labor costs include independent labor cost and labor QA/QC cost. Independent labor cost indicates workers who operate the facility, and are divided into agricultural machine workers, extraction workers, and hazardous material handling workers. The breakdown of independent labor cost is shown in Fig. 4-5.

The distribution of agricultural machine workers, extraction workers, and hazardous material handling workers are about 35%, 45%, and 20% respectively (Fig. 4-5a). These results also reflect the laborer's wages. The general labor wage has doubled since the 1980s, with the wage of an extraction worker increasing the highest increment to over 125% than an agricultural machine worker (about 106%). Therefore, the expense of an extraction worker takes up the majority of labor costs. As capacity is scaled up, the cost of hazardous material workers and agricultural machine workers increase, and the cost of extraction workers decrease (Fig. 4-5b). Based on the importance of desolvenization and solvent recycle for hexane extraction, more hazardous workers are required to assure product quality and safety of operating. Additionally, in the larger scale operations, more agricultural workers are needed to cope with larger amounts of raw materials. The decrease of extraction worker cost demonstrates the high efficiency of the solvent extraction process.

The labor QA/QC cost is estimated as 15% of total independent labor cost. Labor QA/QC is mainly from work, which is required to assure quality of products and is needed for the production stream to prevent revenue deductions from flawed products. According to Fig. 4-3b, as capacity is scaled up the percentage of labor related costs decreases, and becomes the smallest percentage of total operating costs. Fig. 4-3b also indicates the larger capacity process is more material handling intense than labor intense.

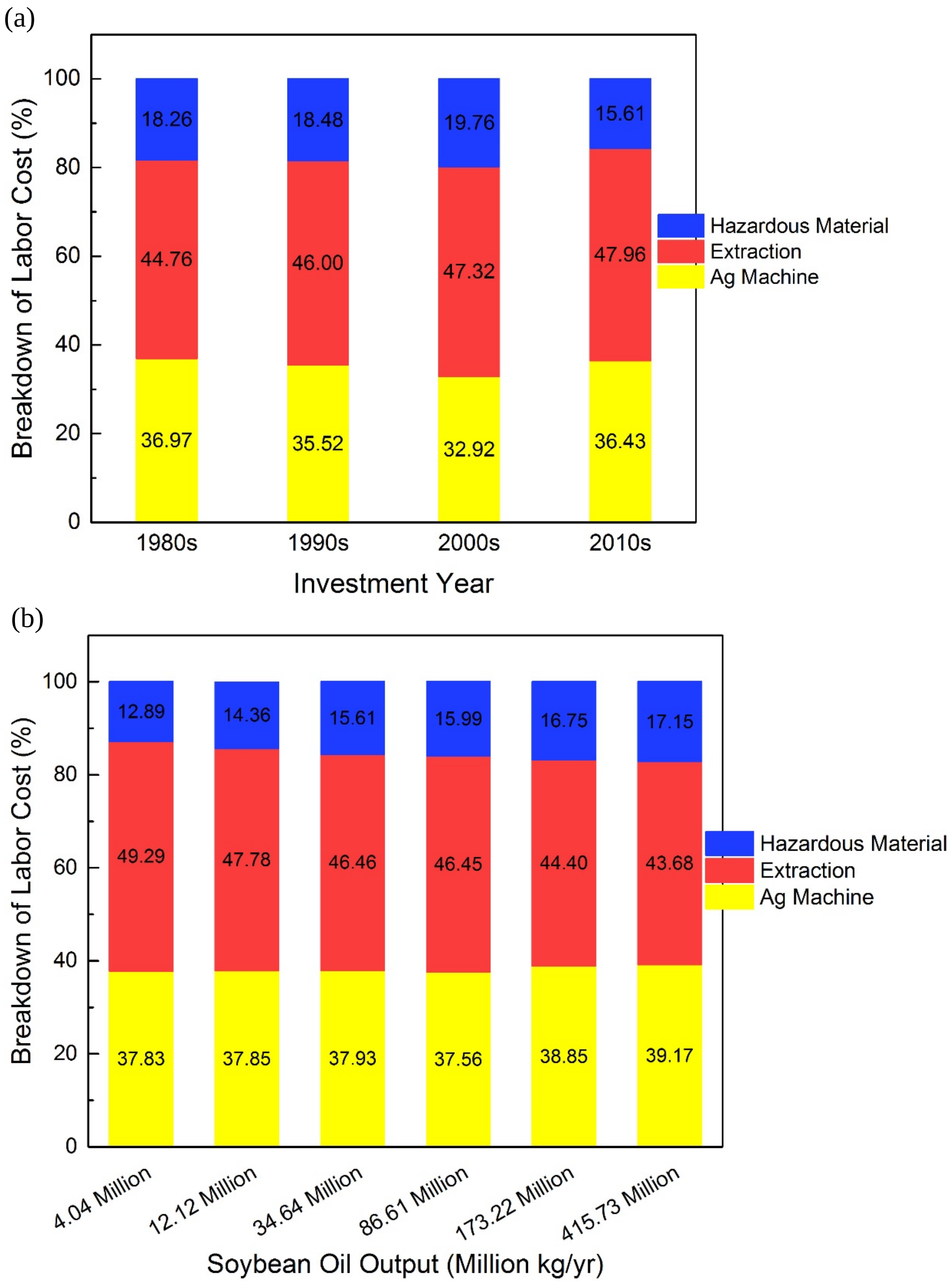

Fig. 4-5 Breakdown of labor costs. (a) 1980-2015 data; (b) Different scales of soybean oil extraction

In the past 30 years, total facility maintenance and repair costs increased due to the increase of fixed cost. In the 2010s, because of higher material costs, the percentage of facility related cost decreased. Otherwise, in different scales of soybean oil production, as the capacity is scaled up, the percentage of facility related costs decrease because higher material and utility costs are needed for larger scale productions of soybean oil.

Considering the relationship between total operating costs and different operating capacities, the operating cost per 1 kg of soybean handling can be calculated. In the hexane extraction process, the unit operating cost is between \$0.46 and \$1 based on operating capacities. Also, there is a -0.15 power relationship between the unit operating cost and different operating scales (Fig. 4-6).

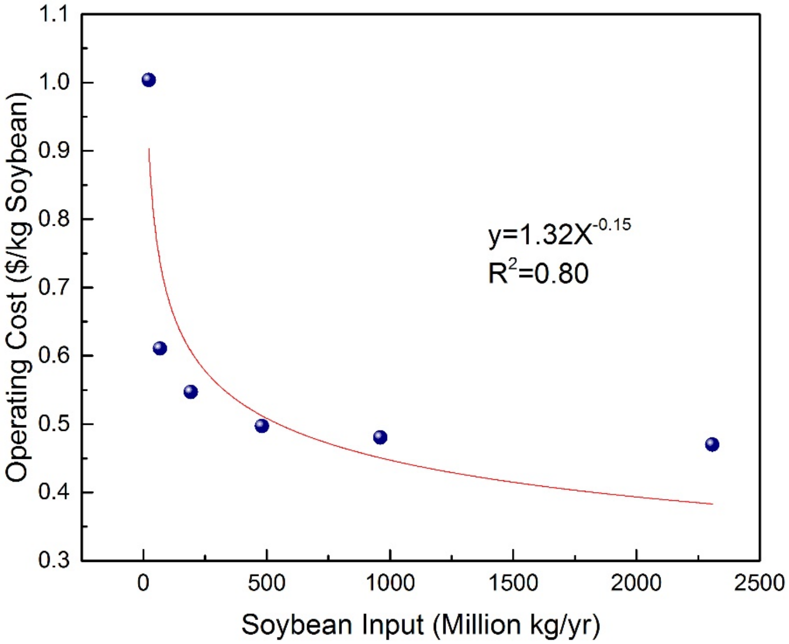

Fig. 4-6 Power relationship between unit operating cost and different operating capacities

3.2.4 Unit Producing Cost

The unit producing cost is calculated by dividing total soybean oil productivity from total operating costs. From 1980s to 2010s, based on the reference scale, the unit producing cost increased from \$1.60 to \$3.04 per 1 kg of soybean oil production due to the changing and increasing value of economic and market conditions.

From the total operating cost results of different scales estimated based on the 2010s market conditions, the unit producing cost is estimated by a power relationship of -0.15 between production scales and cost (Fig. 4-7). As the capacity is scaled up from 4 million kg to 415 million kg of annual soybean oil production, the unit production decreases from \$5.57 to \$2.61 per 1 kg of soybean oil production which are lower than the extruding-expelling process about 23%-33% at similar operating scales.

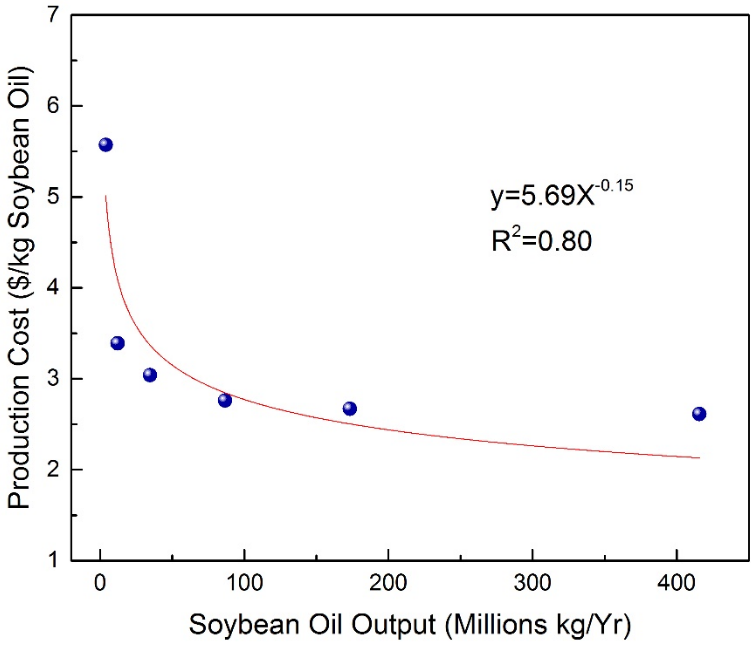

Fig. 4-7 Power relationship between net unit producing cost and different scales of soybean oil extraction

3.3 Revenues

3.3.1 Main Product and Co-Products

Degummed crude soybean oil is the main product of the extraction process. Soybean hulls, obtained from cracking and aspiration, and soybean meal, derived from desolvenization after extraction, are the two co-products of the producing stream.

According to the results, revenue from soybean oil makes up about 39% of total revenues; however, soybean meal and hulls contribute to over 60% of total revenues, with meal taking the largest portion of over 59% of total revenue. Additionally, meal also has the largest portion of total product yields based on weight (over 70%) followed by oil (22-25%) and hulls (3-4%). These results are predicted by the nutrient contents of soybean. Therefore, soybean meal could be regarded as an important driving force for soybean oil production.

3.3.2 Profits

Profits of the operation are estimated based on total revenues and operating costs. The results are shown in Fig. 4-8.

Fig. 4-8a shows the increments of economic and market values. Though there are no positive gross profits and net profits from the 1980s to 2010s in 34.64 million kg of soybean oil production, the lower gross profits and net profits are due to the increase of product selling prices. The increments of gross and net profits also reflect the values of products increased much more than operating costs.

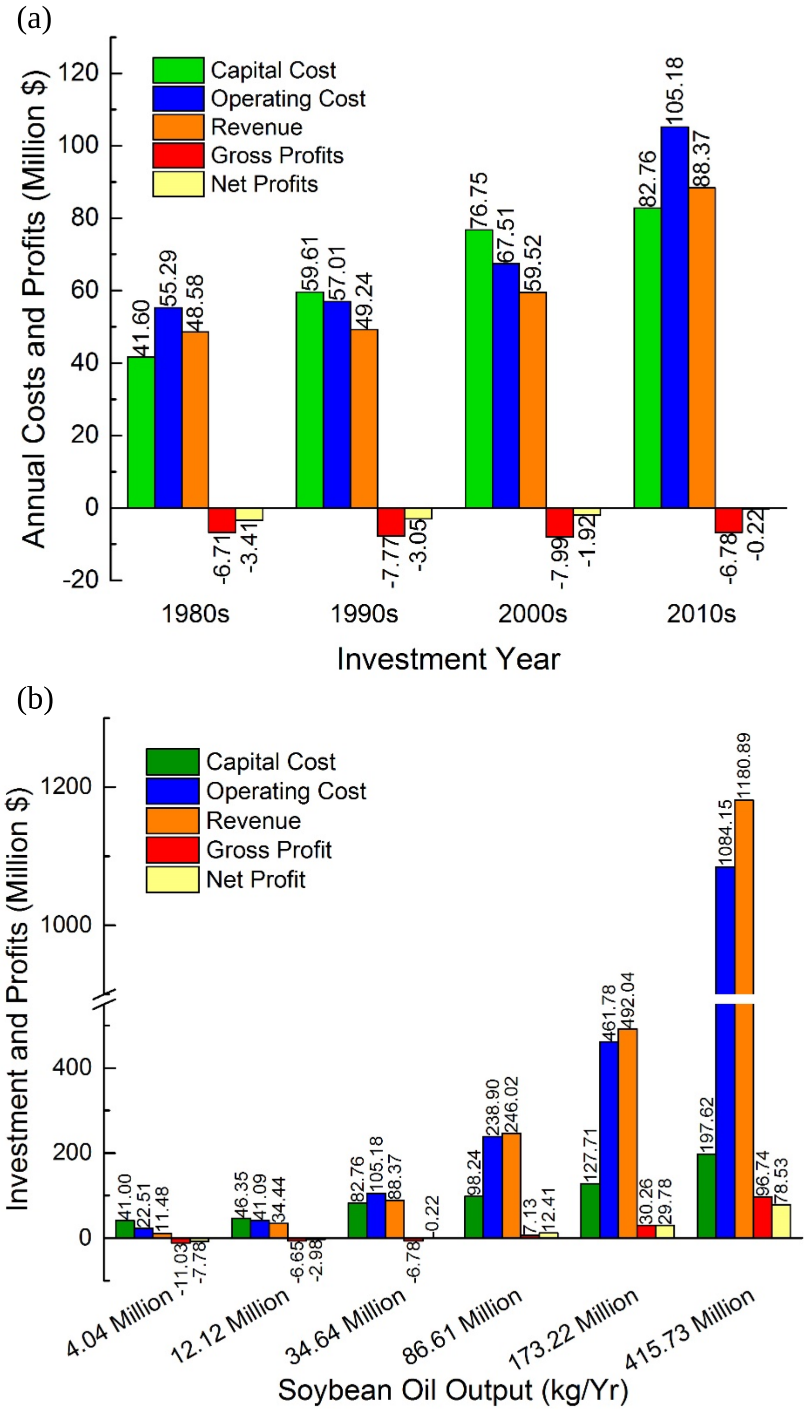

Fig. 4-8 Capital investment, gross and net profits of soybean oil hexane extraction. (a) 1980-2015 data; (b) Different scales of oil extraction

For different scales based on 2010s market estimations, a positive net profit is observed when the capacity is larger than 34.64 million kg of soybean oil production. Positive profits can be obtained when the capacity is scaled up to 86.61 million kg of soybean oil production. These results also indicate the break-even point for hexane oil extraction is over 34.64 million kg annual oil production capacity because the total revenues are close to operating costs.

Additionally, based on gross margin and ROI, the payback time is evaluated (Eq. 8) which indicates how many years are required to earn investments back. The gross margin, ROI, and payback time of different scales of soybean production are presented in Table 4-7. From the ROI, the 34.64 million kg of soybean oil production is close to 0%, which indicates this capacity is close to break-even point to earn profits for paying back the total investment. This also indicates when the capacity is larger than the scale, the production stream starts to earn profits. When the capacity is scaled up to over 34.64 million kg of annual soybean oil production, payback time is allocated within 15 years. This demonstrates the process can earn profits within the plant life time, which is the assumption in this study. Therefore, capacities over 34.64 million kg of annual soybean oil productions are economically feasible operating scales.

$$\text{Payback Time} = \frac{100}{\text{ROI}} \qquad \text{Eq. 7}$$

Table 4-7 Gross margin, ROI and payback time of different scales of soybean oil production

	Soybean Oil Annual Production (million kg)					
	4.04	12.12	34.64	86.61	173.22	415.73
Gross Margin (%)	-96.09	-19.32	-6.88	2.93	6.15	8.19
ROI (%)	-18.98	-6.44	-0.27	12.69	23.32	39.74
Payback Time (yr)	N/A	N/A	N/A	7.88	4.29	2.52

4. Conclusions

Hexane extraction is the most common approach used in the soybean oil production industry. Development of economic, higher capital investments, and operating costs are needed. The changes of capital investment are estimated based on inflation index; while the fluctuation of economic conditions are reflected in the operating costs. As demands of soybean oil have increased, either in food, industry, or bio-fuel applications, many companies plan to expand their production capacity. A profitable producing stream is met when the production capacity increases over 34.64 million kg of soybean oil annually. Additionally, soybean price and material cost play a critical role when determining the profit of the whole production line. Moreover, large amounts of soybean meal production is the main driving force for the soybean oil industry; which contributes over 60% of total revenues even though soybean oil is regarded as the main product of the oil extraction process.

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CHAPTER 5

TECHNO-ECONOMIC ANALYSIS OF SOYBEAN OIL ENZYMATIC ASSISTED AQUEOUS EXTRACTION PROCESS

Modified from a paper to be submitted to *Journal of the American Oil Chemists' Society*

Abstract

Aqueous oil extraction is an approach that could replace organic solvent extraction with water. Compared to typical solvent extraction and expelling processes, aqueous extraction has higher oil yield (over 80%) than the expelling process, and resolve issues resulting from chemical loading and remaining. Proteases improve the breakdown of oil bodies and release free oil. The resulting enzyme-assisted aqueous extraction process (EAEP) includes dehulling, flaking, extrusion, enzymatic extraction, and enzymatic demulsification processes. SuperPro Designer conducted a techno-economic analysis (TEA) of the extraction process. The total capital investment, operation cost, and profits were evaluated. During EAEP, insolubility of water and oil allows the simultaneous extraction of protein and oil. This decreases operation costs, especially the oil purification process, and therefore increases profits made from the main product (soybean oil). This simultaneous extraction also increases the profit towards the co-product, i.e. protein in skim. Additionally, the absence of chemical and enzyme recycling contribute to the better economic value of EAEP. Despite the increase in facility costs due to extraction and demulsification units, the value-added co-product extraction and high free oil yield contribute to the economic feasibility of EAEP in industrial and commercial scale productions.

Keywords: Enzyme-assisted aqueous extraction, Techno-economic analysis, Soybean oil, Skim, Operating costs, Economic feasibility.

1. Introduction

In the soybean industry, oil extraction from oilseeds typically applies an organic solvent extraction, such as hexane, due to its cost-effectiveness and high yield over 95% [1, 2]. However, use of an organic solvent leads to environmental and operational safety issues. Hence, a well-handled facility is required for the process and the higher investment and operating costs are required as well. Unfortunately, there is still the possibility solvents could remain in the process causing food safety and public health problems.

To address these substantial environmental and public health issues, the aqueous extraction process (AEP), a solvent-free extraction process using water as an extraction medium, has been investigated, and applied in various oilseeds [3, 4]. This AEP method is based on the insolubility of oil in the extraction medium rather than its dissolubility, as it is in the hexane extraction process; obtaining the low free oil yield [5, 6]. In soybean oil extraction, the presence of protein (oleosin) interacts with oil bodies in seed cotyledons, resulting in the formation of a stable emulsion, which is responsible for the low amount (60%) of free oil recovery in AEP [4]. In addition, mass transferring is another critical factor in AEP.

The flaking and extruding processes are used as a pretreatment to rupture the cell wall, reduce particle size, and make materials porous increase oil extraction to around 71%. However, that is still far lower than hexane extraction [6, 7]. There are other techniques have been used to disrupt soybean tissue and improve the final oil recovery such as microwave heating [8], ohmic heating [9], and ultrasonication [10].

The enzyme-assisted aqueous extraction process (EAEP) applies an additional step of demulsification to increase the final yield to as much as 90% by denaturing proteins and destabilizing emulsion fraction to release oil [11, 12]. The enzymes can be used depending on the oilseeds and extraction conditions [13]. Generally, protease and lipase are used to break down the structure of cotyledon cell walls and oil body membranes to relase oil. Therefore, the EAEP could extract desired products (oil) and co-products (fiber, protein) simultaneously, requiring no need for post-processing, such as the degumming process in hexane extraction, to recover oil [3]. There are four stages of EAEP, developed by de Moura et al. in 2011 [14], that apply to soybean oil extraction. The stages include (1) mechanical pretreatment (dehulling and soybean flaking by extrusion), (2) enzyme assisted aqueous extraction, (3) separation of cream and co-products (3-way centrifugation) and (4) demulsification of the cream fraction to release free oil. The skim fraction, containing the enzyme, is recycled and reused in the extraction process to increase yields of oil and value-added coproducts.

Soybeans are the main oil crop used in the world, and takes up around 90% of U.S. oilseed production, especially in Illinois and Iowa [15]. Advantages of EAEP includes the environmental friendly process, no additional post processes for oil recovering, simultaneous extraction of co-products; and the process has the potential to reduce environmental impacts and lower capital investment when compared to typical hexane extraction [16]. However, the techno-economic analysis of EAEP is seldom and not well determined. Based on the two stages integrated EAEP of soybean oil extraction, material costs, operation costs, total capital investment are included in this TEA study. Additionally, the feasibility of up scaling EAEP is evaluated in this study according to the assessment of various economic factors. As the TEA model for EAEP is built up, it could provide useful information for food or bioenergy production in the soybean biorefinery.

2. Materials and Methods

2.1 EAEP Process

The EAEP process includes dehulling, flaking, extrusion, aqueous extraction, and demulsification. In this study, a two stage aqueous extraction process was used to improve the oil yield, and the liquid phase from the second stage aqueous extraction was integrated back into the first stage of extraction.

During the process, soybean hulls were separated by aspiration due to their light density and sold as animal feed. Before the extraction process, flaking breaks the cell wall of soybeans to make a substrate porous, improving water and enzymes contact with oil bodies [17]. Additionally, soybean flakes were extruded to enhance the action of enzyme on cell components. The extrusion increases surface area, increases susceptibility of proteins to enzymes, and reduces the stability of the difficult-to-break oil rich emulsions [12]. In the extraction process, the ratio of solid to liquid is 1:6 [14]. After aqueous extraction, the oil-in-water emulsion is formed, and the demulsification is achieved by using proteases to degrade olesion (lipophilic protein surrounding lipid globules) and facilitate oil release [3]. The skim from the first extraction and the final insoluble are regarded as co-products, and are used in corn-soybean integrated ethanol productions [2].

2.2 Computer Modeling

SuperPro Designer v9.0 was used to perform the EAEP for soybean oil production. With this software, processing characteristics, equipment, and economic parameters are defined along with conditions, capacity, and characteristics of each production stream [18, 19].

Based on de Moura’s research [14], 75 kg/hour of soybean input (pilot scale) is used as the base scale with 113.1 thousands kg of annual soybean oil production used for scaling up in 7 scales

(5, 15, 25, 45, 75, 150, 450 scale-up ratios). The model is shown in Figure 5-1. The model was built for 15 years of service time, 30 months of construction, 4 months of startup time, 35% income tax, and a 10-year depreciation period with 5% salvage value of directed cost [20].

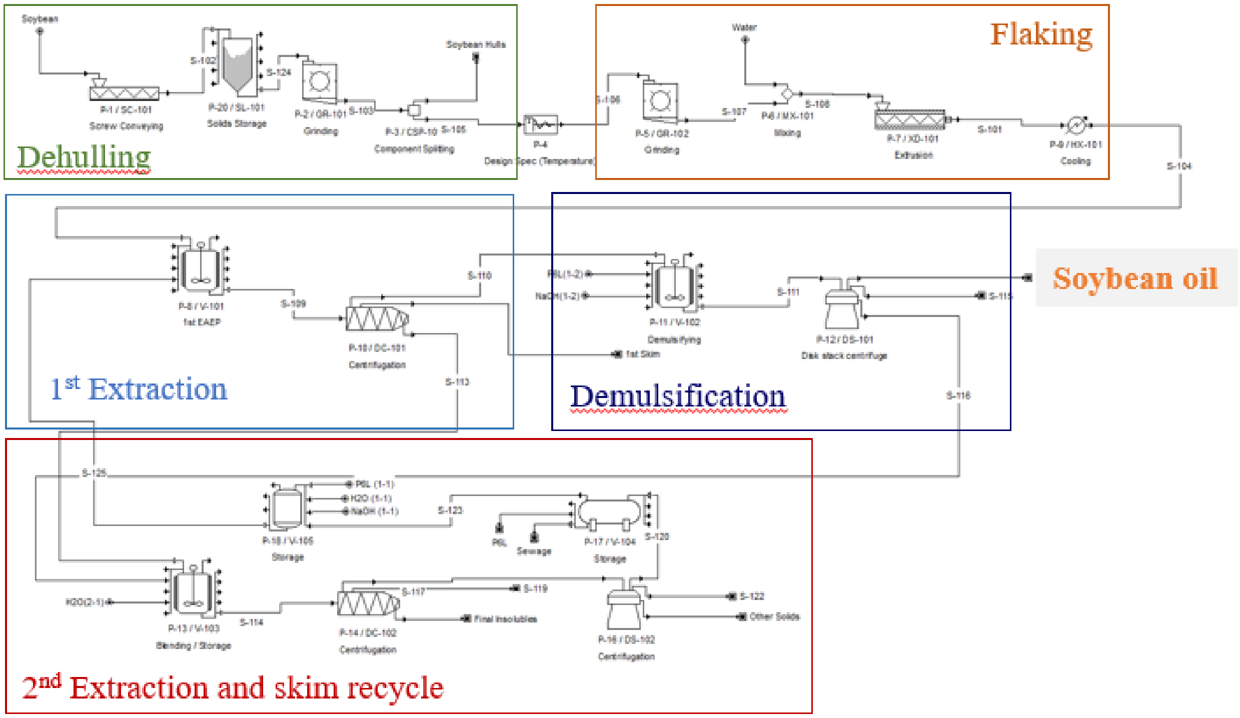

Fig. 5-1 TEA model of EAEP for soybean oil extraction

2.3 Assumption and Data Collection

2.3.1 Fixed Costs

Fixed cost is considered the facility installed for the producing stream. This includes total plant direct cost (TPDC), total plant indirect cost (TPIC), contractor and contingency fees (CFC), startup cost, and working capital, which also depends on the machine's purchase cost (PC). The 2015 purchasing cost of each machine is collected from the inventory record of the Center for Crops Utilization Research (CCUR) pilot, Iowa State University, and SuperPro designer v9.0 database [21].

The machine PC estimation for increased capacities is calculated using Eq. 1 following the power relationship, where PC_p is the machine PC for the predicted capacity, and PC_c is the machine PC of known capacity (basis scale); n is the power used in estimation, generally known as the six-tenths rule (n=0.6) [22]. However, the power (n) varies based on different types of machine, and the estimations of each operating machine are listed in Table 5-1. Additionally, the machine PC is also the basis for estimating the CFC of the total producing stream. The TPDC, TPIC, and CFC are estimated by multiplying the total machine-purchasing price with different multipliers, which are the statistic numbers from chemical and enzymatic processes [23].

$$PC_p = PC_c \times (\frac{q_p}{q_c})^n \qquad Eq. 1$$

Table 5-1 Estimation of facility price for scaling up based on the scale of 0.113 million kg annual soybean oil production (1000 $ based on 2015 price)

	Power	Soybean Oil Annual Production (million Kg)							
	n	0.113	0.565	1.695	2.825	5.085	8.475	17	51
Screw Conveyor*	0.60	5	5	5	5	7	7	9	12
Silo/Bin*	0.60	77	77	77	77	77	77	5	5
Grinder●	N/A	10	10	10	10	10	10	10	10
Flake miller●	N/A	6	6	6	6	6	6	6	6
Aspirator	N/A	13	13	13	13	13	13	13	13
Extruder (drive feeder+ extruder)●	0.60	197	197	197	197	242	242	242	308
Blending Tank I●	0.49	26	63	88	123	152	195	268	443
Blending Tank II●+		13	26	26	35	48	62	87	148
Blending Tank III●+		16	40	62	78	107	125	181	292
3-phase Decanter I●	0.49	130	130	183	223	313	369	564	901
3-phase Decanter II●+		83	83	130	134	223	256	402	590
Disc-stack centrifuge I*	0.60	91	91	91	104	185	185	290	550
Disc-stack centrifuge II*+		104	104	201	273	415	528	800	1,452
Storage Tank*	0.49	26	26	51	57	80	98	126	201
Receiving Tank*	0.54	55	152	221	292	424	617	768	1,390
Unlisted equipment*	0.60	193	282	340	407	575	697	961	1,475

●: Data collected from CCUR pilot inventory, Iowa State University; *: Data collected from SuperPro v9.0 data base [21]; +: Estimated by power relationship (Eq.2) based on pilot scale; and powers (n) were collected from the research of Peters et al., (2011) [22].

2.3.2 Operating Costs

In this model, operating costs include raw material cost, labor cost, facility maintenance cost, and utilities. Soybeans and water are the main sources of material cost for EAEP oil extraction. Additional material costs include sodium hydroxide (NaOH) and protease (Protex 6L) which are used in the extraction and demulsification processes. Electricity is the main energy source, while steam and cooling water are heat transfer agents. Additionally, labor costs are also considered in the modeling. The unit cost input of materials, utilities, and labor are listed in Table 5-2. The energy consumption inputs are listed in Appendix Table A-3.

Table 5-2 Operating costs inputs (All inputs are 2015 prices)

		Cost	Unit	Citation
Materials	Soybean	0.351	$/kg	[15]
	Water	0.00079	$/L	[24]
	Sodium hydroxide	20	$/kg	[25]
	Protex 6L	19.42	$/kg	Quote from DuPont Pioneer
Utility	Electricity	50.5	cents/kwh	[26]
	Steam	12	$/MT	[21]
	Cooling water	0.05	$/MT	[21]
Labor	Agricultural machine operator	14.9	$/hr	[27]
	Extraction worker	22.49	$/hr	[27]

Labor costs include the cracking, aspiration, tempering, flaking, and extrusion of the soybean handling processes and are operated by agricultural machine operators. Water extraction, demulsification, and oil separation, including centrifuging and decanting, are operated by extraction workers. The labor requirements for each processes equipment is between 0.1-1 (workers/unit/shift) for an eight hour shift as a basis scale listed in Table 5-3. However, the relationship between labor requirements and the capacity of production is not linear, and a 0.2-0.25 power of the capacity ratio is applied in plant scale-up estimates [22]. In this study, a 0.25

power is used for optimal estimation. Additionally, the laboratory quality control and assurance cost are also considered and set as 15% of total labor cost (TLC) [23].

Table 5-3 Labor requirements for each operating unit (workers/unit/shift)

	Soybean Oil Annual Production (million kg)							
Operating units	0.113	0.565	1.695	2.825	5.085	8.475	17	51
Conveyor	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
Silo	1	1	1	1	1	1	1	1
Cracking	1	1	1	1	1	1	1	1
Aspirating	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Flaking	1	1	1	1	1	1	1	1
Extrusion	1	1	1	1	3	3	3.48	4.57
1st stage extraction	1	2	2.24	2.24	2.72	2.8	3.29	4.26
1st Centrifuging	0.2	0.4	0.4	0.4	0.56	0.56	0.66	0.85
Demusification	1	1.6	1.68	1.68	2.24	2.4	2.66	3.34
1st Decanting	0.2	0.2	0.24	0.24	0.24	0.24	0.36	0.44
2nd stage extraction	1	2	2.24	2.24	2.88	3.04	3.50	4.47
2nd Centrifuging	0.2	0.4	0.4	0.4	0.56	0.56	0.69	0.84
2nd Decanting	0.2	0.4	0.4	0.4	0.4	0.4	0.47	0.62
Storage (sewage)	1	2	2.4	2.4	3.04	3.2	3.56	4.16
Storage (skim recycle)	1	2	2.4	2.4	3.28	3.36	3.98	4.39

Labor requirement indexes were set based on different machine [22, 28]

Besides materials, utilities, and labor costs; machine maintenance, insurance, and local tax are also included. However, these costs all depend on DFC, and are estimated as 7%, 1% and 2% of DFC respectively for the chemical and enzymatic processes [23].

2.3.3 Revenues

Soybean oil is the main product of the EAEP process and soybean hulls, separated during aspiration, are one of the co-products. Additionally, skim, generated from centrifugation after the water extraction, is used as a water supply for integrated cellulose ethanol production, and its selling price is evaluated by water price. The final insoluble fractions from the EAEP, has high fiber (CHO) and can be used as the fiber resources for cellulose ethanol production. The Protex 6L was recycled to reduce material cost, and is regarded as a saving credit. Therefore, skim and final insoluble fractions are considered potential co-products, which increase the revenues of the whole process. Their selling prices are: soybean oil (0.81 $/kg, [15]); soybean hulls (0.21 $/kg, [29]); skim (0.0079 $/L, [24]); insoluble fiber (0.6 $/kg, [30]); Protex 6L (19.42$/kg, quote from DuPont Pioneer).

According to annual operating costs and revenues, the total profit is considered and the gross profit and gross margin percentages are calculated based on Eq. 2 and Eq. 3. Also, the net profit, including taxes and depreciation (Eq. 4) is calculated. Return on investment (ROI) is also calculated based on net profit and total capital investment (Eq. 5).

$$Gross\ Profit = Total\ Revenue - (Total\ operating\ cost - credits) \qquad Eq. 2$$

$$Gross\ Margin\ (\%) = \frac{Gross\ profit}{Revenue} \times 100\% \qquad Eq. 3$$

$$Net\ Profit = Gross\ profit - Taxes + Depreciation \qquad Eq. 4$$

$$Return\ on\ Investment\ (\%) = \frac{Net\ profit}{Total\ capital\ investment} \times 100\% \qquad Eq. 5$$

3. Results and Discussions

3.1 Total Capital Investment

Total capital investment is divided into direct fixed capital (DFC), working capital (WC) and start-up capital (SC). The facility purchasing cost (PC) is the basis for total capital investment estimation; and consists of main machines and unlisted machines, as well as motors, pumps, and other auxiliary components [22].

Table 5-4 shows the estimation of total capital investment of eight scales using EAEP in soybean oil production. The total plan direct cost (TPDC) includes installation, processing piping, instrumentation, and insulation; and are all estimated using machine purchase price (PC). Indirect cost covers plant planning, construction, and organization; which indicate engineering and construction costs are estimated based on TPDC. Besides direct and indirect costs, contractor and contingency fees are also included in DFC, which allow for additional costs resulting from unexpected events during the lifetime of the project [23].

Before the production line starts to work making products, a validation process is essential for all facilities, and covers process, operation, and installation qualification. The validation process is considered a start-up cost; however, during the start-up period, consumption of raw materials, energy, and consumables are counted as working capital. These detailed costs are all covered in the total capital investment estimation as well.

Table 5-4 Total capital investment breakdown of three scales of EAEP (1000 $)

			Soybean Oil Annual Production (million kg)							
Costs	Categories	Multipliers*	0.113	0.565	1.695	2.825	5.085	8.475	17	51
Total Plant Direct Cost (TPDC)	Purchase cost (PC)		971	1,261	1,701	2,033	2,877	3,487	4,803	7,373
	Installation	0.47×PC	456	593	799	956	1,352	1,639	2,258	3,465
	Process piping	0.68×PC	660	857	1,157	1,383	1,956	2,397	3,266	5,013
	Instrumentation	0.26×PC	252	328	442	529	748	907	1,244	1,917
	Insulation	0.08×PC	78	101	136	163	230	279	384	590
	Electrical	0.11×PC	107	139	187	224	316	384	528	811
	Buildings	0.18×PC	175	227	306	366	518	628	865	1,327
	Yard improvement	0.10×PC	97	126	170	203	288	349	480	737
	Auxiliary facilities	0.55×PC	534	693	935	1,118	1582	1918	2,642	4,055
	TPDC	2.43×PC	3,329	4,324	5,834	6,974	9,867	11,960	16,476	25,288
Total Plant Indirect Cost (TPIC)	Engineering	0.30×TPDC	999	1,297	1,750	2,092	2,960	3,588	4,943	7,586
	Construction	0.35×TPDC	1,165	1,514	2,042	2,441	3,454	4,186	5,766	8,851
	TPIC		2,164	2,811	3,792	4,533	6,414	7,774	10,709	16,437
Total Plant Cost (TPC)	TPDC+TPIC		5,493	7,135	9,625	11,507	16,281	19,735	27,185	41,725
Contractor’s fee and Contingency (CFC)	Contractor’s fee	0.06×TPC	330	428	578	690	977	1,184	1,631	2,503
	Contingency	0.08×DFC	494	642	866	1,036	1,465	1,776	2,175	3,755
Direct Fixed Cost (DFC)	TPC+CFC		6,316	8,205	11,069	13,233	18,723	22,695	30,991	47,983
Working Capital (WC)		0.15×DFC	947	1,231	1,660	1,985	2,808	3,404	4,649	7,197
Startup Capital (SC)		0.05×DFC	316	410	553	662	936	1,135	1,550	2,399
Total Capital	TPC+CFC+WC+SC		7,580	9,847	13,283	15,880	22,468	27,234	37,189	57,580

According to the results of total capital investment estimation for eight scales, TPDC takes up a majority of total investment with around 45%; TPIC, CFC, WC, and SC take around 29%, 11%, 13% and 4% of total capital investment individually. Comparing the total capital investment among these eight scales, the capacities were 113,000; 565,000; 1,695,000; 2,852,000; 5,085,000; 8,475,000; 17,000,000 and 51,000,000 kg of soybean oil production with the total capital investment of \$7,580,000; \$9,847,000; \$13,283,000; \$15,880,000; \$22,468,000; \$27,234,000; \$37,189,000; and \$57,580,000 respectively which are lower than the extruding-expelling process and hexane extraction process. Additionally, the total capital investment has a power relationship of 0.35 (R^2=0.96) with annual soybean oil productivity (Fig. 5-2), and the equation for scaling can be expressed in Eq. 6; where CI and CP indicate capital investment and capacity of the producing line. The footnotes of i and p represent basis (initial) and predicted scales of the producing line.

$$CI_p = CI_i \times 0.82 \left(\frac{CP_p}{CP_i}\right)^{0.35} \qquad Eq.6$$

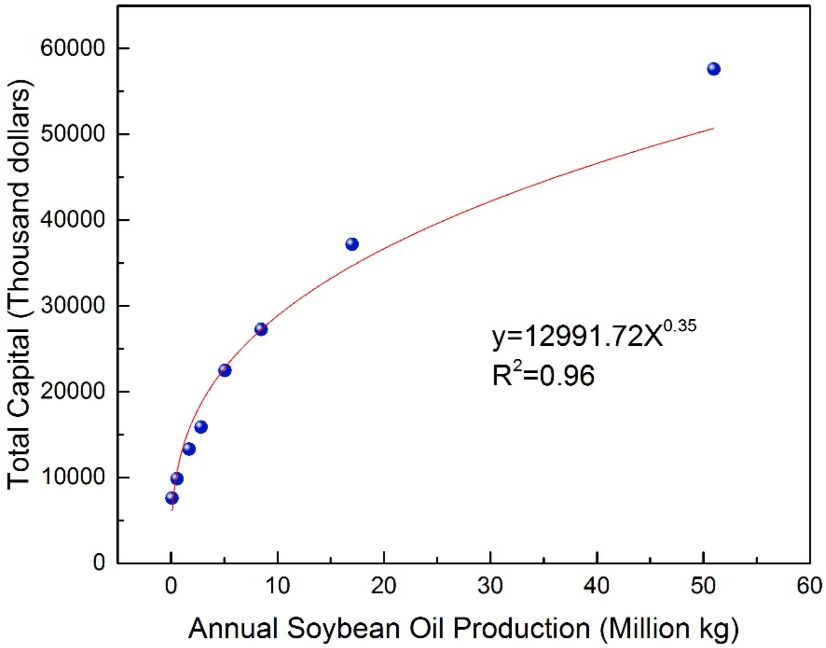

Fig. 5-2 Power relationship between total capital investment and different scales of soybean oil production

3.2 Operating Costs

Material, utility, labor related (labor independent, labor QA/QC), and facility related (maintenance) costs are considered operating costs. However, their distribution proportions to operating costs change as the production line is scaled up. Fig. 5-3 shows the breakdown of operating costs. In the basis scale (0.113 million kg of soybean oil annual production), facility costs take up over 60% of all operating costs; which mainly consist of facility maintenance fees. Labor related costs are another major source of operating expenses; achieving over 20% of total operating cost. By contrast, as the processing capacity is scaled up, the material cost becomes the major component of operating costs; totaling over 80% of all expenses while all others are below 10%. This result indicates small capacity processing is much more facility and labor intense, is producing less efficiently, and the same amount of laborers could handle more duties in a larger capacity.

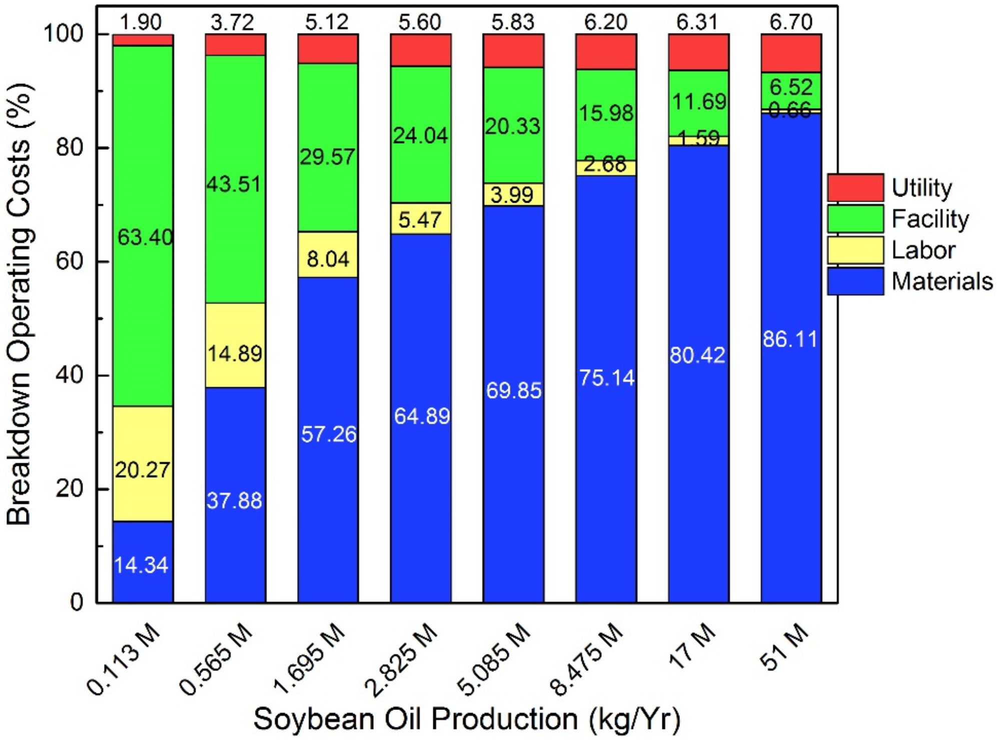

Fig. 5-3 Breakdown of operating costs

3.2.1 Material Costs

Soybeans and water are the main materials in EAEP for soybean oil production, with the enzyme, Protex 6L, used to assist oil release. Without Protex 6L, sodium hydroxide is used in pH adjustment during the extraction and demulsification processes. The breakdown of each material in the whole production stream are: sodium hydroxide (10N): 8.17%, Protex 6L: 30.68%, soybeans: 60.45%, and water: 0.7%. However, among these materials, Protex 6L, which has the highest purchase price of $19.42/kg, took over 30% of total material cost. As the capacity increase, more materials are required for the producing line. Thus, the material cost is a critical factor in large -scale production lines.

3.2.2 Utility and Labor Related Costs

Utility costs consist of electricity, steam, and water. Electricity is the main energy resource to power machines used in the producing stream. Steam and cooling water are heat transfer agents, especially in the evaporation and cooling processes. In EAEP, labor costs can be divided into two main processes: crops handling and extraction. Crops handling is also regarded as material preparation for the further extraction, including crop cleaning, drying, flaking, tempering, and extrusion. Extraction includes water extraction, demulsification, and oil separation. Based on the assumption of this TEA model, agricultural machine workers are assigned to the crops handling process, and extraction workers operate extraction, demulsification, and oil separation. Fig. 5-4 shows the breakdown of utility and labor costs of EAEP soybean oil production.

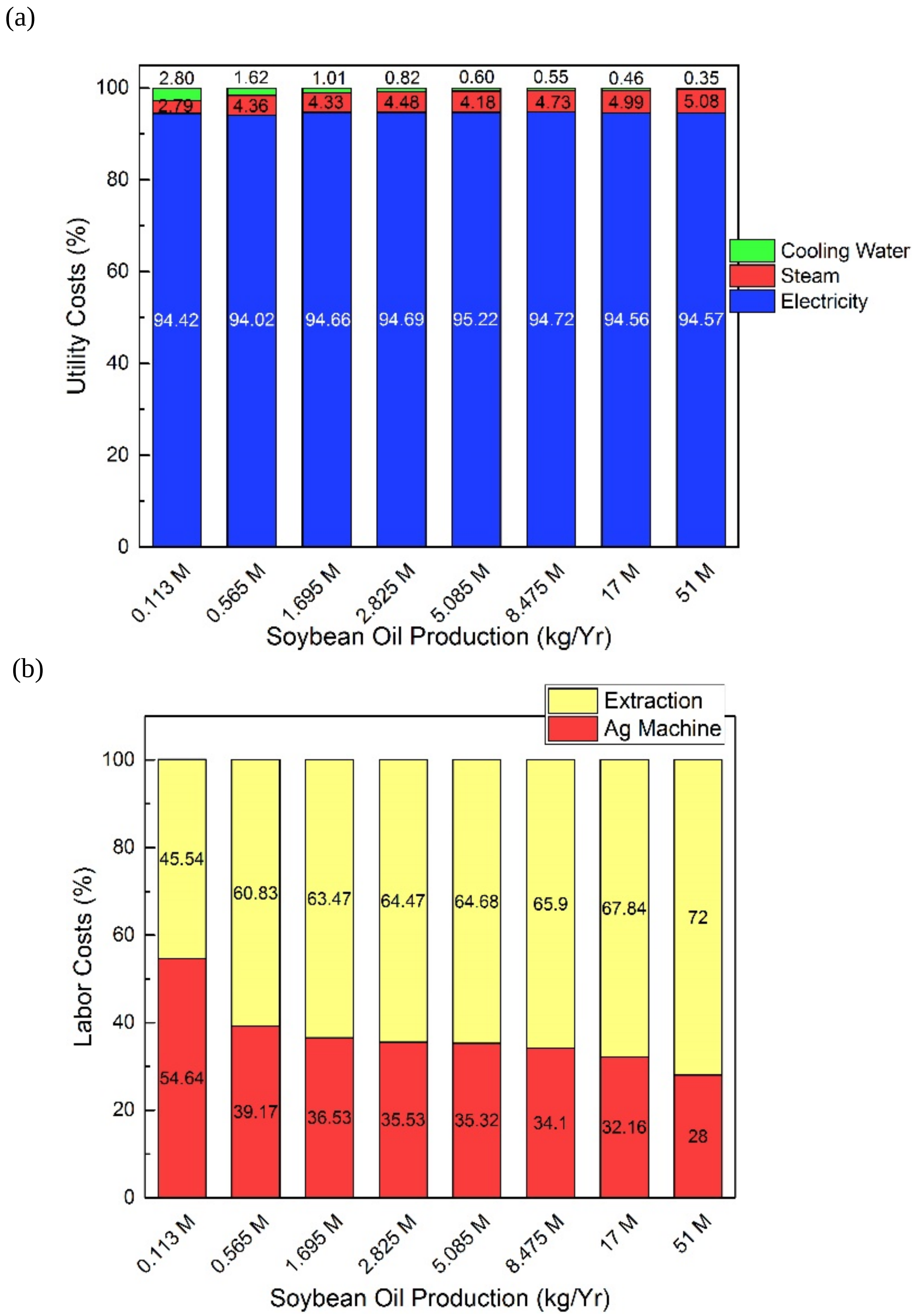

Fig. 5-4 Breakdown of utility costs (a) and labor costs (b)

Fig. 5-4a represents the breakdown of utility costs for eight scales. The percentage of electricity consumption decreases as the capacity is scaled up, though the increase was not obvious. For steam usage, as the capacity increases, more steam is required during processing. However, the electricity consumption follows closely to the linear relationship as the ratio of capacity scaling up between electricity usage and a ration of capacity scaling up.

Fig. 5-4b illustrates the percentage of labor costs in different scales of soybean oil production. From the results, the agricultural machine workers take over 50% of total labor costs in the small (basis) scale but the extraction workers take the majority of labor costs in larger scale productions. This result indicates that as the capacity is scaled up, more extraction workers are required. This corresponds to the larger amounts of oil/water emulsion, which are handled in larger amounts of oil production. It also reflects the enzyme assisted extraction requires a skilled extraction worker.

For labor QA/QC cost, it was estimated by the total labor cost (TLC) to be 15%, and there were $65,000; $90,000; $96,000; $96,000; $117,000; $122,000; $134,000; and $158,000 for 0.113, 17, and 51 millions kg of annual soybean oil productions. Facility cost, mainly from machine maintenance fees, were $1,584,000; $2,010,000; $2,712,000; $3,242,000; $4,587,000; $5,560,000; $7,539,000; and $11,756,000 for 0.113, 0.565, 1.695, 2.825, 5.085, 8.475, 17, and 51 million kg of annual soybean oil productions respectively.

3.2.3 Unit Net Producing Cost

Based on fixed, operating costs and main product (soybean oil) annual production, the unit net production costs of several scales are calculated (Figure 5-5). According to the results, the unit cost decreases with a power of -0.51 when more soybean oil is produced. In 51 million kg of annual soybean oil production, the unit net production cost decreases from \$20.6/kg to \$2.6 per kg soybean oil production.

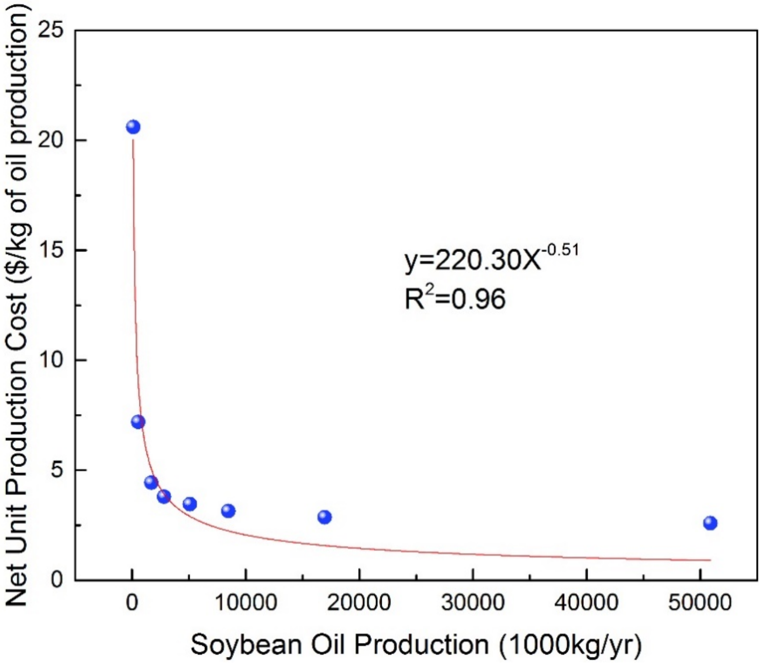

Fig. 5-5 Power relationship between net unit producing cost and soybean oil production

3.3 Revenues and Profits

3.3.1 Revenues

Soybean oil is the main product of EAEP, and coproducts include soybean hulls, skim and insoluble fiber. For soybean hulls, it is generated from aspiration process, and it could be sold as animal feeds. For skim and insoluble fiber, based on the assumption of this model, the oil extraction is a part of integrated soybean/corn based ethanol production process. Thus, skim is used as water supply, and the protein content could help the further fermentable sugar fermentation [2]. Also, the insoluble fiber is reused in the ethanol production. Therefore, these two materials are considered as the coproducts of the EAEP. However, Protex 6L are recycled during the extraction and demulsification processes to reduce operating cost. Hence, recycled Protex 6L is regarded as the saving of whole producing line.

From the results, soybean oil takes around 27% of total revenues; the revenue from insoluble fiber takes over 70% due to its large amounts produced from the process. Additionally, the coproducts for further integrated soybean/corn based ethanol production take around 74%. Therefore, it is obvious to see the oil production process especially using enzyme assisted process can not totally rely on the revenue from oil product. In other words, these co-products make themselves as the incentive for the oil extraction process. However, the saving from enzyme recycled also reflects the high cost of enzymatic process again. If the enzyme is not recycled and reused, it would lead to high operating cost and it is difficult to earn profits from producing line.

3.3.2 Profits

Profits of the EAEP process are divided into gross profit and net based in Eq. 2 and Eq. 4. From the results are shown in Fig. 5-6, the scales below 8.475 million kg of annual oil production have negative gross profit, indicating the producing stream is unable to earn profits back to investment. However, capacity over 17 million kg of annual oil production is able to earn profits with recycling enzymes used in the extraction and demulsification processes. Therefore, the smaller scale operations of oil production using the enzyme-assisted method are economically unfeasible. Although the scale of 8.475 million kg oil production has negative gross profits, it is still profitable when its net profit is considered by adding depreciation fees. Additionally, this scale is close to the breakeven point, having both positive gross and net profits. Comparing to the extruding-expelling process, the net profit is lower about 37%-55% at the similar operating scales.

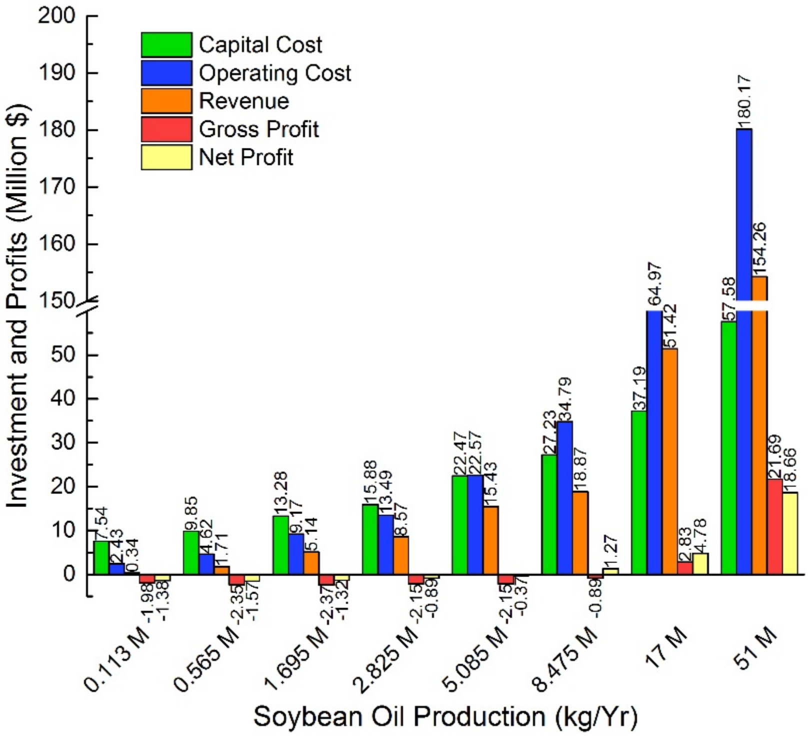

Fig. 5-6 Capital investment, gross profit and net profit of EAEP

When comparing capital cost to operating cost in each scale, operating cost starts to overpass capital cost in scales over 5.085 million kg of annual soybean oil production. As stated in previous discussion, large-scale capacities require higher operating costs; especially material cost, which take up over 80% of total operating costs. Operating cost fluctuates with different process designs and economic condition changes, which have a direct influence on gross and net profits of a producing line. Therefore, operating cost is always a critical issue for industrial and commercial scale productions.

The gross margin and ROI is calculated according to profit, capital investment, and total revenues. The gross margin is the ratio between the gross profit and revenue, and ROI represents how the plant earns the investment back. According to the ROI, payback time is estimated using Eq. 7, and indicates how many years it takes to earn profit back. The gross margin, ROI, and payback time of these eight scales of oil producing lines are shown in Table 5-5. Results indicate scales below 5.085 million kg of annual oil production are still losing money on the investment due to negative values of gross margin and ROI. A scale of 8.475 million kg of annual oil production has 21.52 years of payback time, which is still too long to earn money back even though it has a positive ROI. As the scale expands to 17 and 51 million kg of annual oil production, both gross margin and ROI are positive; and the payback time is shorter than assumed service time. These results indicate larger production scales have a profitable potential, and the production line starts to earn profits at the 8th and the 3rd year.

$$\text{Payback Time} = \frac{100}{\text{ROI}} \qquad \text{Eq. 7}$$

Table 5-5 Gross margin, ROI and payback time of different scales of EAEP used in soybean oil production

	Soybean Oil Annual Production (million kg)							
	0.113	0.565	1.695	2.825	5.085	8.475	17	51
Gross Margin (%)	-579.8	-137.29	-46.05	-25.08	-13.93	-3.46	5.50	14.06
ROI (%)	-18.31	-15.98	-9.91	-5.62	-1.65	4.65	12.86	32.40
Payback Time (yr)	N/A	N/A	N/A	N/A	N/A	21.52	7.78	3.09

4. Conclusions

EAEP is an innovative process for oil extraction. However, the operating costs are still the main problem stopping EAEP from becoming a practical production stream. If only the main product, soybean oil, is relied on for profits, it could merely provide 27% of total revenues. To improve the economic feasibility of EAEP, the pretreatment of integrated soybean/corn based ethanol production and co-products from the oil extraction processes are considered. Skim and insoluble fibers generated from the process are sold as materials for further ethanol production to improve overall revenue. The application of Protex 6L is another critical issue for EAEP because it contributes to a large proportion of operating costs. Therefore, recycling Protex 6L with skim is an essential process and is seen as another saving credit of operating costs, making EAEP more feasible in a commercial scale. Results show small scale production is unfeasible to be applied in the industry; however, EAEP has the potential to combine with further integrated ethanol productions in a commercial scale setting.

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CHAPTER 6

CASH FLOW ANALYSIS

Modified from a short communication to be submitted to the *Journal of the American Oil Chemists' Society*

Abstract

Soybean oil production is the main process used for in soybean applications. Cash flow analysis estimates the profitability of a manufacturing venture. Besides capital investments, operating costs, and revenues, the interest rate estimates the net present value (NPV), break-even point, and payback time; which are benchmarks for profitability evaluation. The positive NPV and reasonable payback time represent a profitable process, and is an acceptable projection for real operating. The capacity of the process is also another critical factor. The extruding-expelling process and hexane extraction are the two typical approaches used in the industry. When the capacities of annual oil production are larger than 4.1 and 173 million kg respectively, these two processes are profitable. The solvent free approach, known as enzyme assisted aqueous extraction, is profitable when the capacity is larger than 17 million kg of annual oil production.

Keywords: Soybean oil, Profitability, Cash Flow Analysis, Interest rate, Net Present Value, Payback Time

1. Introduction

For a manufacturing venture, the capital investment, operating costs, revenues, ROI and other indicators shown in Chapter 3-5 are used to evaluate the general profitability. The money sink throughout the service time of the project is another critical factor when estimating the profit of the process. The cash flow analysis performs money sink and costs of various resources of capital; which are also able to predict the total profit at the end of plant lifetime.

The concept of cash flow is illustrated in Fig. 6-1. This project can be divided into four periods: construction, validation, manufacturing, and shutdown. The cash inflow in the construction period is mainly from capital investment (direct fixed cost). In the validation period, working capital, startup cost, and the rest of capital investment are cash inputs. As the process starts to operate, the operating costs are the cash inflow; while revenues and depreciation are defined as the cash output. In the shutdown period, operating costs and revenues are the cash input and output respectively. Additionally, the salvage of the capital investment and the working capital are compensated in the last year of the service time (Ulrich, 1984).

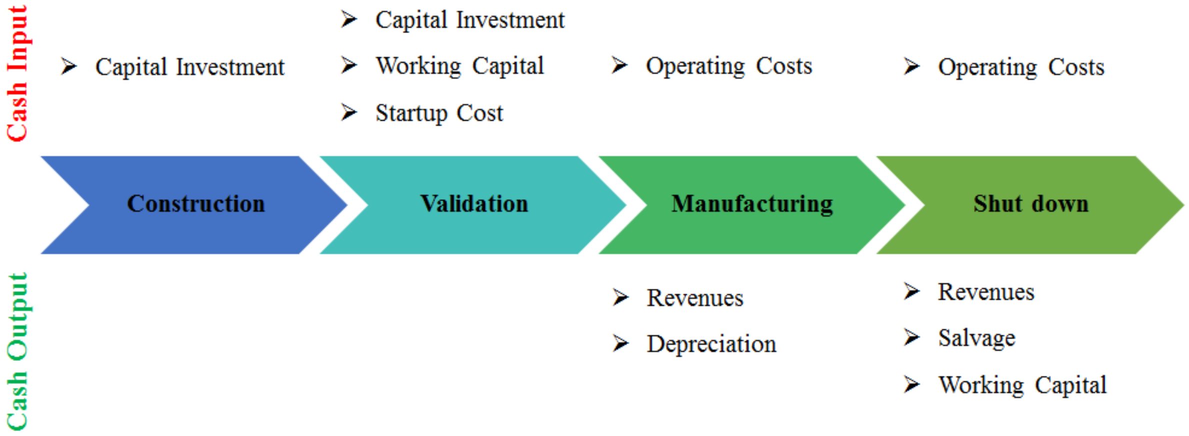


Fig. 6-1 Schematic flow of cash flow analysis

Time-value of money (TVM) is another critical factor for profit estimation. TMV means the value of money is not fixed but fluctuates with time and economic conditions; therefore, it should be thought of as a commodity, and has time-depending value (Ulrich, 1984). In other words, a dollar earned today has a higher value than a dollar earned in 15 years of the plant's life time. The estimation of TVM is based on the interest rate (Ulrich, 1984; Heinzle et al., 2006), and the calculation is shown in Eq. 1. C_t and C_0 are the capital in the investment year (t) and the current year respectively; i represents the interest rate.

$$C_t = C_0(1+i)^t \qquad Eq.1$$

Based on the revenues and profits earned during the process, the TVM also converts to a recent value for the profitability prediction. It is interpreted as "How much money must be invested today to have the equal capital in the 't' years?" TVM is calculate by reversing Eq. 1 to solve the C_0, and is also expressed by a discount factor (f_d) (Eq. 2).

$$C_0 = \frac{C_t}{(1+i)^t} = C_t \times \frac{1}{(1+i)^t} = C_t \times f_d \qquad Eq.2$$

The TVM is used to estimate the "net present value" (NPV), which also estimates the profitability of the process. NPV is the difference between the accumulative discounted cash flow and total investment expressed in Eq. 3 (Peters et al., 2011). Positive NPV means the process is profitable and vice versa. Therefore, a process with a positive NPV should be expected to operate.

$$NPV = \sum_{1}^{t} C_t f_d - Capital\ Investment \qquad Eq.3$$

A similar concept is used for the internal rate of return (IRR) estimation. IRR is the indicator used to describe the interest rate at which the NPV is equal to 0. In other words, when the IRR of the process is larger than the interest rate (i) used for the profitability estimation, the process is profitable. Equation 3 is also used for the IRR calculation. In the calculation of IRR, NPV is replaced by 0, and the interest (i) can be solved as the IRR.

The TEA results shown in Chapter 3-5 are based on basic profit estimation without considering interest rate effects. The cash flow analysis is used to show the profitability of extruding-expelling, hexane extraction, and EAEP for soybean oil extraction.

2. Analysis Methods

2.1 Assumptions

The assumptions are based on the TEA model built for extruding-expelling, hexane extraction, and EAEP as shown in Chapter 3-5. The construction period is 30 months, with annual investments of 30%, 40%, and 30% of DFC in the first three years respectively. The startup period is 4 months; depreciation (DE) is 10 years with a straight-line method; and, salvage (SV) is 5% of DFC. The interest rate (i) is 7%. These assumptions are based on general chemical and bioprocess operating (Heinzle et al., 2006).

2.2 Cash Flow Calculation

Based on the total capital investments, operating costs, and revenue estimations from Chapter 3-5, cash flow is estimated following Table 6-1. Gross profit (GP) and net profit (NP) are calculated first; with the net cash flow (NCF) obtained by adding capital investment (CI), GP, and NP. The cumulative cash flow (CCF) is the sum of the NCF from each year. CCF in the last year of plant service also represents the NPV without considering the interest (i).

When the interest is considered, the discounted cash flow (DCF) is calculated by multiplying NCF with f_d. The cumulative discounted cash flow (CDC) is obtained using the same methods as CCF calculations. The last year of CDC is the NPV of operating. Also, the IRR is obtained from SuperPro Designer model simulation.

Table 6-1 The calculation of cash flow for soybean oil extraction investment

Investment year	Capital investment	Operating costs	Revenues	Gross profit	Tax	Depreciation	Net profit
	CI	OC	RS	GP	T	DE	NP
1	30% DFC	0	0	OC-RS	0	0	GP-T+DE
2	40% DFC	0	0	.	0	0	.
3	30% DFC+ WC+SC	2 months OC	2 months RS	.	35% GP	95% DFC/10	.
4	0	OC	RS	.	.	.	.
5	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
13	.	.	.	.	.	0	.
14	.	.	.	.	.	0	.
15	WC+SV	.	.	.	.	0	.

Table 6-1 Continued

Investment year	Net cash flow	Cumulative cash flow	Discount factor	Discounted cash flow	Cumulative discounted cash flow
	NCF	CCF	f_d	DFC	CDC
1	CI+NP	∑NCF	(1/1.07)^t	NCF×f_d	∑DFC
2	.	.	.	.	.
3	.	.	.	.	.
4	.	.	.	.	.
5	.	.	.	.	.
.	.	.	.	.	.
13	.	.	.	.	.
14	.	.	.	.	.
15	.	.	.	.	NPV

The estimations of CI, OC, RS, GP, T, and NP are based on the results derived from Chapter 3-5.

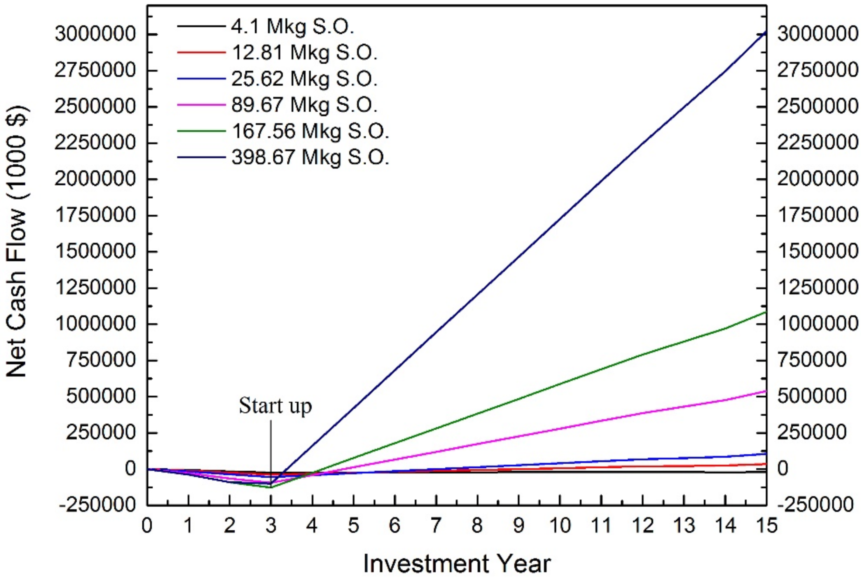
3. Results and Discussions

3.1 Extruding-Expelling Process

The cash flow of the extruding-expelling process investment is shown in Fig. 6-2. Results show the extruding-expelling process is profitable when the capacity is scaled up to 12.81 million kg of annual soybean oil production. This result is observed when interest is considered as well.

From the results, the payback time and break-even point of the investment is also observed. The scale of 12.81 million kg of annual soybean oil production is used for further discussion (Fig. 6-3). From Fig. 6-3, the cash outflow before the first three years indicates investments for total capital mainly come from DFC. After the third year, the cash inflow shows the process starts to earn revenues from products. The peak point demonstrates the startup time of the plant. When the net cash flow meets 0, the point is defined as a break-even point. Therefore, the distance between startup time and break-even point is the payback time of the process. The NPV is the net cash flow of the last year of plant life time.

(a)



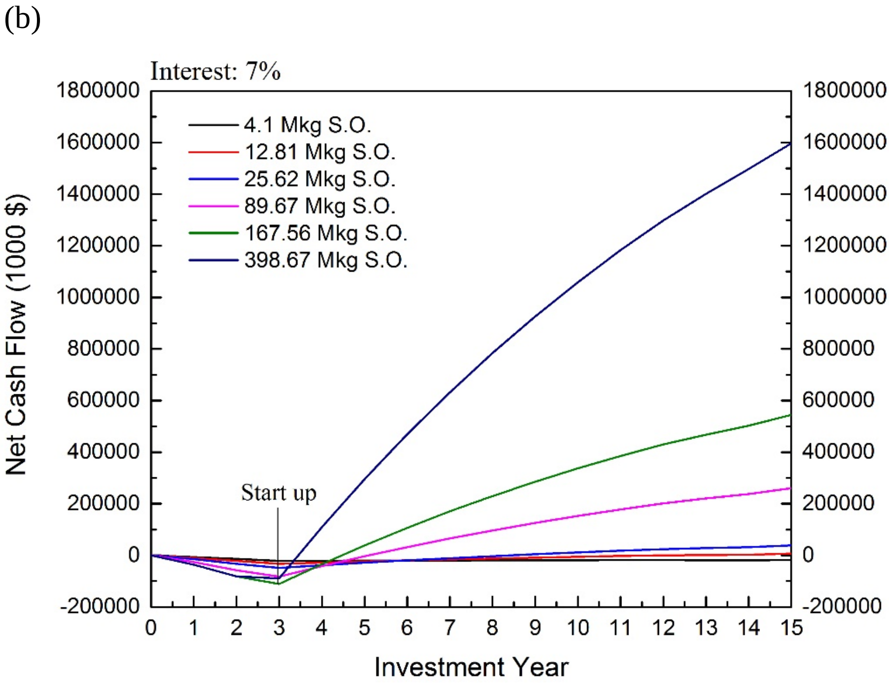


Fig. 6-2 Cash flow of extruding-expelling process. (a) interest rate is not considered; (b) 7% interest rate included. (S.O. indicates the annual soybean oil production)

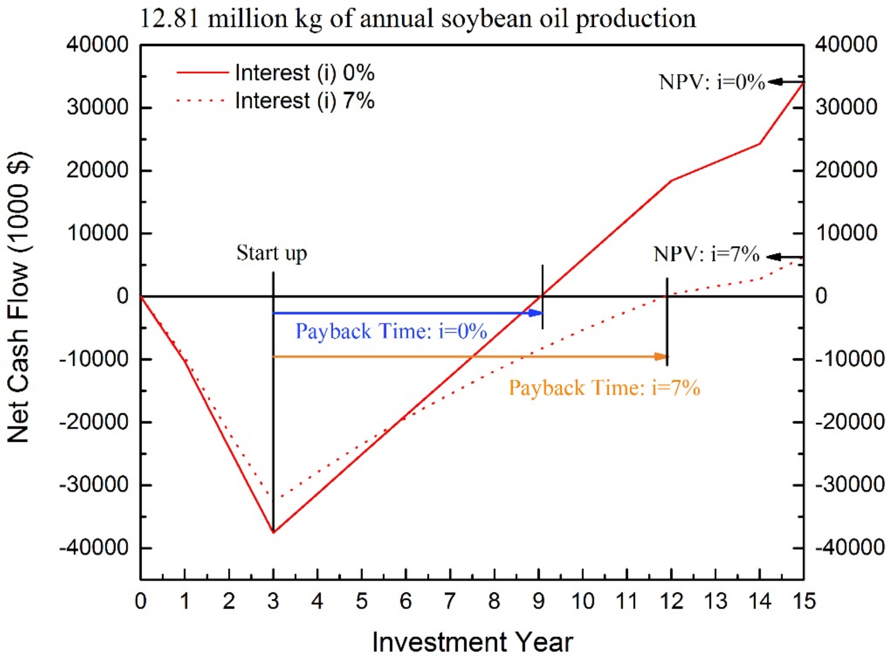


Fig. 6-3 The profile of cash flow

From Fig. 6-2 and Fig. 6-3, the longer payback time and lower NPV is observed when the interest rate is considered. The longer payback time and lower NPV is expected when larger interest is applied. In addition to the effect of the interest rate, the larger capacity plants result in shorter payback time and higher NPV.

According to the assumed 7% interest rate, the NPV of these six scales are -18319, 6307, 38263, 260420, 544552, and 1597494 thousand dollars. The IRR of each capacity larger than 4.1 million kg of annual soybean oil production is predicted as larger than 7%. Based on the results of the simulation, the IRRs of 12.81, 25.62, 89.76, 167.56, and 398.67 million kg of annual soybean oil production are 8.83%, 22.27%, 36.80%, 48.05%, and 93.83% respectively. Conclusively, capacity scales larger than 4.1 million kg of annual soybean oil production are profitable.

3.2 Hexane Extraction

According to the results from Chapter 4, the capacity with positive net profit was chosen for the cash flow analysis, and the result is shown in Fig. 6-4. Fig. 6-4 shows the trends of interest rate and capacity effects are similar to those of the expelling process. The larger capacity plants, without considering interest rate, result in higher NPV and shorter payback time. For the capacities of 173.22 and 415.73 million kg of annual soybean oil production, positive NPVs are observed when the interest rate is included, and are 83229 and 353252 thousand dollars individually. The IRRs are 17.27% and 30.55% with payback times of about 2.5 and 3.5 years respectively after the plant is started up. Therefore, these two scales are accepted for the real operation projections.

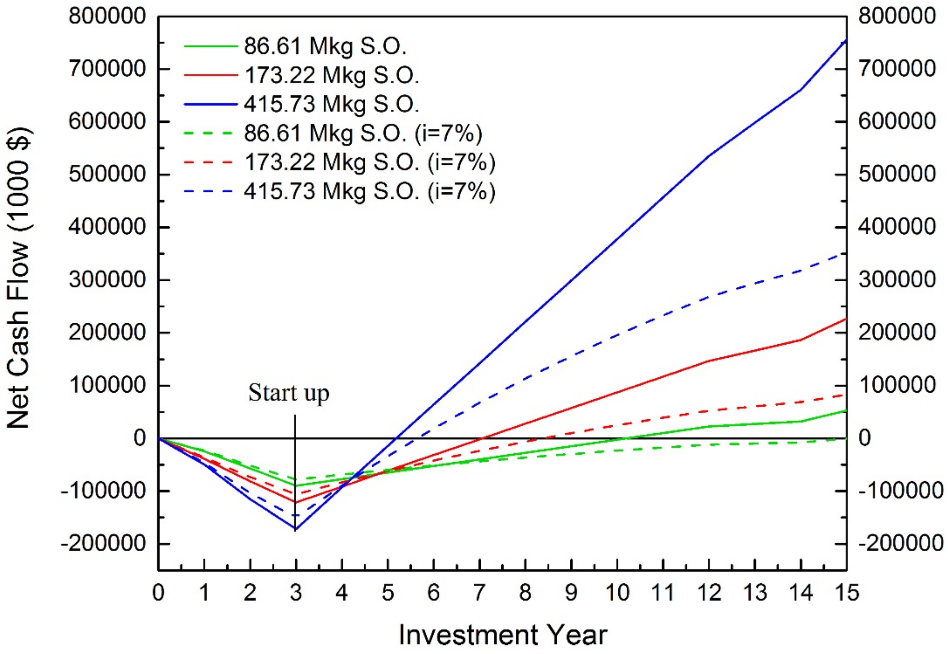


Fig. 6-4 Cash flow of hexane extraction. (S.O. indicates the annual soybean oil production)

The production scale of 86.61 million kg of annual soybean oil production is estimated as a profitable process, with a positive net profit and NPV based on results from Chapter 4. However, when the interest rate is considered, the NPV is -$283,000. It is risky to take this scale into operation. Based on the results of the simulation, the NPV of this scale is close to 0, indicating its IRR is pretty close to 7% at 6.48%.

3.3 EAEP

Based on the results in Chapter 5, scales with positive net profits were chosen for the cash flow analysis. The results in Fig. 6-5 show similar trends are observed. Although the scale of 8.48 million kg of annual soybean oil production has a positive profit, negative NPVs are observed for both cases, with and without considering interest rate. This scale is not profitable in real operation.

For scales of 17 and 51 million kg of annual soybean oil productions, positive NPVs are obtained. They are 20808 and 169114 thousand dollars when no interest rate is included; and 307 and 74957 thousand dollars when the interest rate is considered. Additionally, these two scales have reasonable payback times, which are about 3.5 and 12 years after the plant starts to produce products.

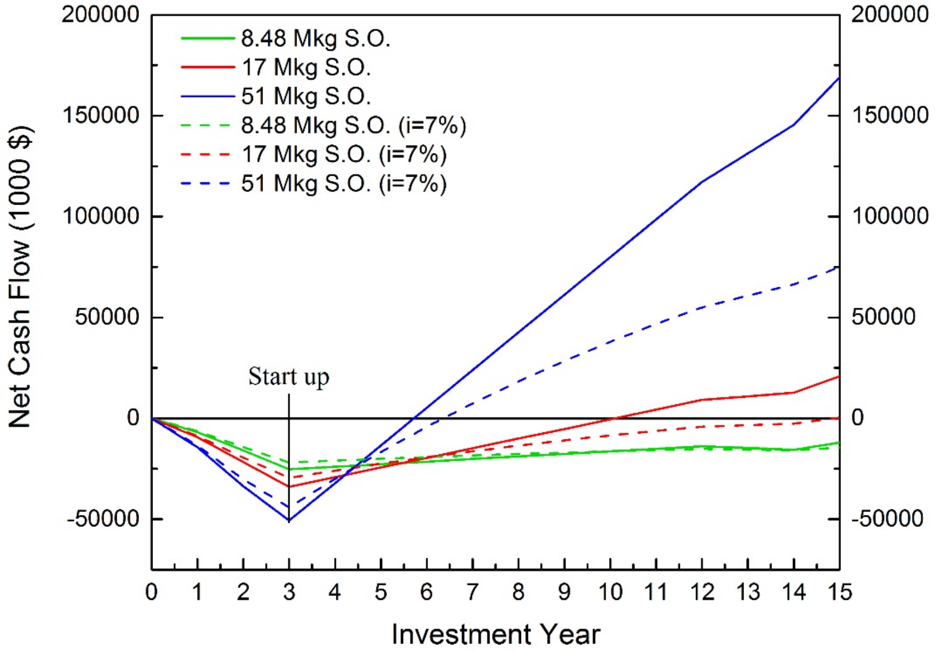


Fig. 6-5 Cash flow of EAEP. (S.O. indicates the annual soybean oil production)

About 11% of the IRR is achieved for the 51 million kg of annual soybean oil production scale. In the scale of 17 million kg of annual soybean oil production, the IRR is little bit larger than 7% because the NPV is close to 0. Fig. 6-6 illustrates how to predict the IRR for the EAEP process. The positive NPV indicates the IRR is larger than 7. The 7.5% interest rate was tried and applied to the analysis, and a negative NPV was obtained. Therefore, the IRR of this scale is between 7-7.5%.

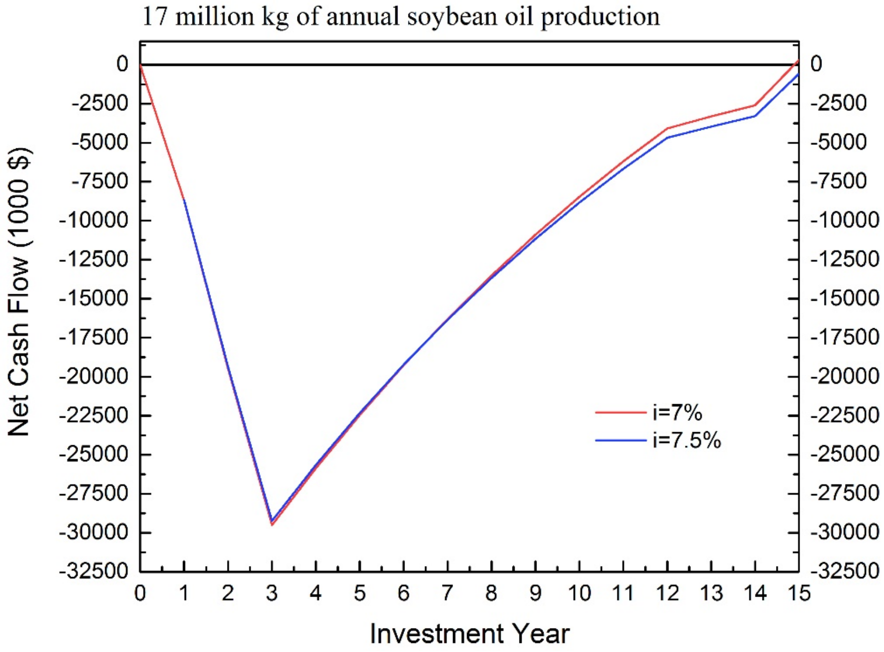


Fig. 6-6 IRR prediction for EAEP

4. Conclusions

From the results of cash flow analysis, the effect of interest rate and the flow of cash banks are observed. The payback time and the break-even point are also illustrated. The extruding-expelling process is profitable when the scale is over 4.1 million kg of annual soybean oil production. In the hexane extraction, the scales of 173.22 and 415.73 million kg of annual soybean oil productions are profitable in real operations due to positive NPV at a 7% interest rate. Though the positive net profit and NPV without considering interest rate is obtained in the scale of 86.61 million kg of annual soybean oil production, the NPV turns negative when the interest rate is included. This indicates this process cannot be profitable in real operations. As to EAEP, similar trends to the hexane extraction are observed. The scales of 17 and 51 million kg of annual soybean oil productions are profitable in real manufacturing. In addition to the net profit and ROI used for estimating the profitability of the process, cash flow analysis is another critical indicator for predicting the profitability of a manufacturing venture based on the flow of annual capital banks.

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CHAPTER 7

SENSITIVITY ANALYSIS

Modified from papers of extruding-expelling process, hexane extraction, and EAEP to be submitted to the *Industrial Crops and Products and Journal of the American Oil Chemists' Society*

1. Introduction

In the soybean oil extraction process, further applications of soybean oil bring other economic values. Therefore, oil extraction is seen as the first step of the soybean refinery process. However, the co-product of the extraction process, soybean meal, contributes over 50% of total revenues (refer to the results of extrusion-expelling and hexane extraction) because its high protein content is a resource for animal feeds.

To estimate the economic feasibility of soybean oil extraction processes, the operating costs and retail price of products are the main factors according to profit calculations discussed in chapter 3-5. However, operating costs and selling prices fluctuate with economic and market conditions; especially soybeans, soybean oil, and soybean meal prices. Fig. 7-1 illustrates the annual production of soybeans and the prices of beans, meal, and oil from 1980 to 2015.

The economics of soybeans, soybean meal, and soybean oil closely relate to supply and demand. Fig. 7-1 shows the following trend: more soybeans produced equals lower prices of beans, meal, and oil. Motivations causing soybean production changes are shifting demand drivers, new competition, and high oil and meal prices. Shifting demand drivers are the end use or related industry demand changes, such as changing food products, biodiesel, livestock productions, and export demand. New competition refers to the application of other oil crops; and the high oil and meal prices drive more crop productions (Biodiesel.org, 2011).

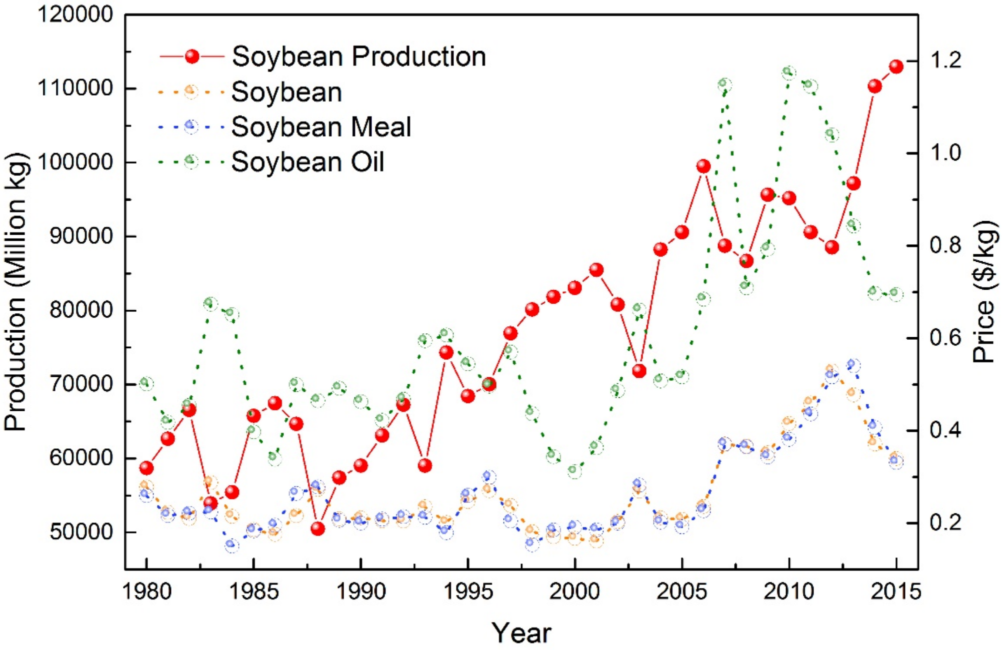


Fig. 7-1 The annual production of soybean and the prices of soybean, soybean meal and soybean oil (USDA ERS, 2016)

In addition to the supply and demand of soybeans, interactions between products and co-products also influence the prices of meal and oil. The basic rule of thumb is as follows: when demand for one co-product decreases, the price of the other co-product increases with everything else remaining equal (Biodiesel.org, 2011).

Besides material costs and revenues obtained from products, other operating costs play a critical role in the profits of an oil extractiom operation. Some research focuses on the effect of energy consumption patterns for soybean production (Ramedani et al., 2011), the optimization of energy consumption for soybean production (Mousavi-Avval et al., 2011; Zhang et al., 2015), and the economic and environmental effects of soybean farming (Kamali et al., 2017). However, there is no research focusing on the operating cost and product effects on the oil extraction process.

The sensitivity analysis is used to perform operating costs and product effects on all three extraction processes. The driving factor and force of the process is also examined.

2. Analysis Methods

Referring to the TEA models used for oil extractions (Chapter 3-5), sensitivity analysis is performed to examine the factor that has the most significant effect on changing net profits of a process with fluctuating economic conditions. Table 7-1 illustrates ±5%, ±15% and ±25% changes in operating costs; including material, labor, utility, facility related costs, and revenues from the operation. The sensitivty analysis is based on the 2010s economic conditions.

As the net profit is obtained, three different scales of oil production with positive net profits were chosen for analysis. The net profit change is presented in percentages, which are calculated according to Eq. 1.

$$Net\ Profit\ Chnage\ (\%) = \frac{Difference\ of\ Net\ Profit}{Original\ Net\ Profit} \times 100\% \qquad Eq. 1$$

Table 7-1 Operating cost and product factors for oil extraction sensitivity analysis

	Extrusion-Expelling	Hexane Extraction	EAEP
Operating Costs	Raw materials Utility Labor Facility related	Raw materials Utility Labor Facility related	Raw materials Utility Labor Facility related
Renvenues	Soybean oil Soybean meal	Soybean oil Soybean meal Soybean hull	Soybean oil Soybean hull Skim Insoluble fiber

3. Results and Discussions

3.1 Extruding-Expelling Process

According to the results of net profit and payback time, the extruding-expelling process has high potential to be economically feasible. The annual soybean inputs of 96.14, 672.99 and 2991.93 million kg, which have 12.81, 89.67, and 398.67 million kg of annual soybean oil outputs, are chosen for the sensitivity analysis. Sensitivity analysis examines which factor included in operating costs and revenues has the most significant effect on net profit when the cost and selling price fluctuate with economic and market conditions. The results are shown in Fig. 7-2. When operating costs (including material, labor, and utilities) increases, the net profit decreases; which is shown in the negative bar (yellow bar) and vice versa.

The larger range of change in operating costs and selling prices leads to larger changes in net profits. In these three scales, soybean meal has the most remarkable effect on the net profit in all levels of price changes, followed by soybeans and then soybean oil. This indicates soybean meal plays an important role in the process, and is seen as the driving force for the extrusion-expelling technique used in the industry. Additionally, as the scale of capacity increases, the level changes of net profit caused by price changes decreases.

In the aspect of operating costs, soybeans and electricity are the two factors that have the most obvious effect on net profit changes. This also demonstrates the property of a mechanical process. However, as the capacity is scaled up, more energy demands are required for the producing stream; especially when cooling water, which cools down the system after heat is generated from extrusion. Therefore, the effect of cooling water exceeds the labor cost, and follows electricity cost when the capacity is scaled up. Additionally, higher amounts of phosphoric acid are required in the degumming process for a larger plant capacity. The effect of phosphoric acid cost exceeds the labor cost at the largest operating scale. This result corresponds to the previous discussion about the portions of each operating cost.

Overall, extruding-expelling is a product leading process; especially the revenue from soybean meal. However, the material cost from soybeans still plays a critical role in determining the profit of the whole process. These results show the uniqueness of the extrusion-expelling process; which still exists in the industry even though solvent extraction is applied more recently due to its high efficiency.

3.2 Hexane Extraction

Since positive net profits are obtained from scales of 86.61, 173.22 and 415.73 million kg of annual soybean oil production, a sensitivity analysis is used to examine which factor affects the net profit the most. The results are shown in Fig. 7-3. As operating costs, including materials, utilities, and labor increase, the net profit decreases; which is shown in a negative bar (yellow bar) and vice versa.

From the results shown, the more changes applied for operating costs and products selling prices, more changes of net profit are observed. For 86.61 million kg of annual soybean oil production, soybeans have the most significant effect on the net profit, followed by soybean meal and oil. This indicates material cost is more important than products in net profit estimation. In products, soybean meal has a more significant effect than soybean oil in all levels of selling price changes. Also, as the changes increase from 5% to 25%, the differences in net profit derived from meal and oil effects increase. For 173.22 and 415.73 million kg of annual soybean oil productions, similar trends are observed.

Comparing net profit changes among different capacities, larger scales have less change for net profit as operating costs and products’ selling prices fluctuate. Additionally, the order of effects derived from operating costs and products' selling prices are almost the same for these three scales. In material cost, soybean prices are followed by products, utility costs, and labor costs. However, in the largest scale of 415.73 million kg of annual soybean oil production, the labor cost becomes the factor with the least effect. This indicates a relatively less labor intense process with more energy inputs required for larger scales of a producing stream. Additionally, though steam is an important agent in the drying and desolvenization processes, electricity is used to function all machines. Therefore, electricity has a higher effect on cost than processing and using steam.

Conclusively, soybean cost, soybean meal, and soybean oil selling prices are critical factors for the soybean oil extraction process. Lower soybean prices and higher meal and oil selling prices are desired. Though soybean oil is the main product of the producing stream, soybean meal is regarded as the driving force for the soybean oil production industry due to its higher productivity and higher revenues than soybean oil.

3.3 EAEP

Based on the results of net profit, scales of 8.475, 17, and 51 million kg of annual soybean production are chosen for sensitivity analysis, and the results shown in Fig. 7-4. Operating costs and revenues are compared and included in tornado figures. However, operating costs shown in increase (red) bars mean the costs were lowered 5%, 15%, and 25% and vice versa.

Fig. 7-4 shows changes of net profit increase when a portion of each operating cost and revenue rise; however, as the capacity of operation is increased, the effects from operating costs and revenues are decreased. In 8.475 million kg of annual soybean oil production, all 11 factors have the same order of ±5%, ±15%, and ±25% for operating costs and revenues changes. Insoluble fiber has the most significant effects of all factors; the net profit decreases about 356% as the retailed price is 25% lower than the 2015 price. The effects of products on net profit change show insoluble fiber has the highest impact, followed by soybean hull and soybean oil; with the revenue from skim having the least effect on net profit change. This result indicates the main product, soybean oil, is not the main driving force of the whole process; and co-products provide more profits than main product. As to operating costs, soybeans have the largest effect on net profit change; followed by insoluble fiber, and soybean oil. This result reflects the operating scale relies more on revenues, especially profits from co-products.

For 17 million kg of annual soybean oil production, insoluble fiber is still the most important factor for net profit change. As the capacity of a producing line is scaled up, the effect of soybean oil follows insoluble fiber in product factors. Soybeans still have the main effect on net profit change for operating costs. When the capacity of a producing line is scaled up, more material and energy are required; causing higher operating costs. Therefore, chemical cost, sodium hydroxide, and electricity cost have more effect than soybean hull on net profit change. Similar results are observed in 51 million kg of annual soybean oil production. However, larger amounts of skim generated from the extraction process contribute to higher revenues than smaller scales of producing lines; and, therefore, it has more effect than labor cost.

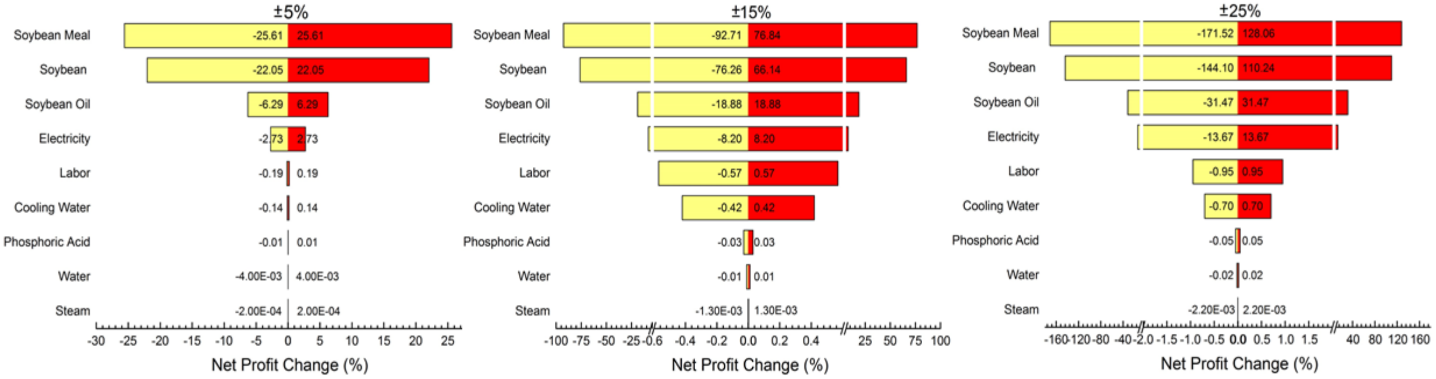
Additionally, though the cost of the protease (Protex 6L) takes up about 30% of the total material cost, it is recycled with skim to reuse in the extraction and demulsification processes. Thus, there is no effect in net profit changes as enzyme costs change. Conclusively, results reflect the driving force of EAEP used for soybean oil production is not dependent on the main product, but co-products; especially insoluble fiber due to its high retail price. Results also show EAEP has the potential to earn profits when it provides insoluble fiber as a resource for further ethanol conversion processes.

4. Conclusions

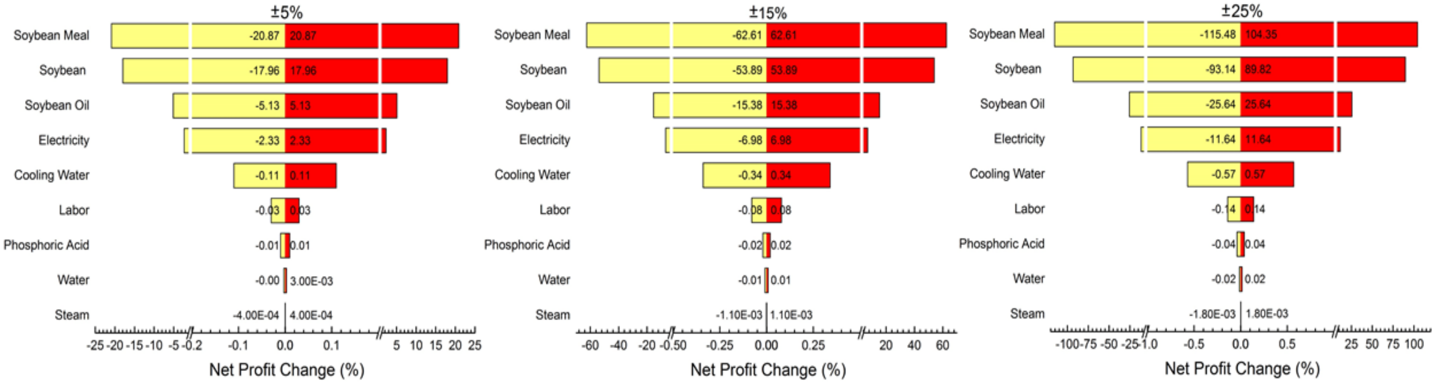
In oil extractions, soybean cost and revenues from co-products have significant effects on profits. For the extrusion-expelling process, soybean meal has the most obvious effect on net profit change. This result indicates the expelled soybean is the main driving force of the operation, and also demonstrates the specific application of expelled meal for livestock feeds (Nelson et al., 1987). For hexane extraction, soybean cost is the leading factor of the process. However, soybean meal has a higher effect than soybean oil on the net profit. Therefore, soybean meal produced from mechanical expelling and hexane extraction contribute more profits than soybean oil; and is mainly used for animal feed applications due to high protein content and other nutrition advantages (Lawrence et al., 2003; Wang et al., 2004).

Though there is no meal produced from the EAEP operation, insouble fiber, used as a carbohydrate resorce for corn-soybean integrated bioethanol refinery (Sekhon et al., 2015), is the major factor affecting net profits. Otherwise, EAEP has similar trends as the extruding-expelling process which are product leading processes. Conclusively, though soybean oil is regarded as the main product of oil extraction operations, co-products contribute the major revenues. Therefore, co-products and their further applications are the driving forces of oil extraction processes.

(a) 12.81 million kg of annual soybean oil production



(b) 89.67 million kg of annual soybean oil production



(c) 398.67 million kg of annual soybean oil production

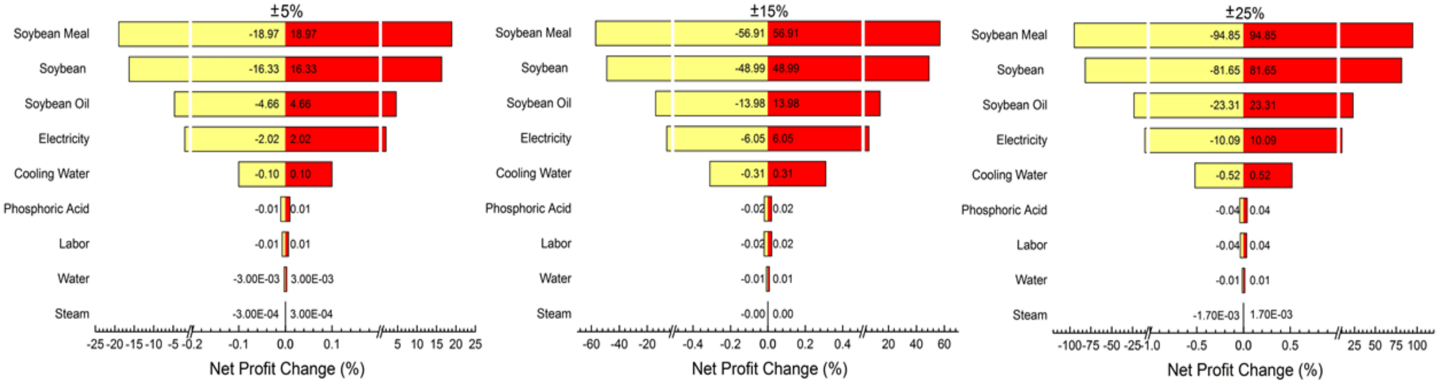
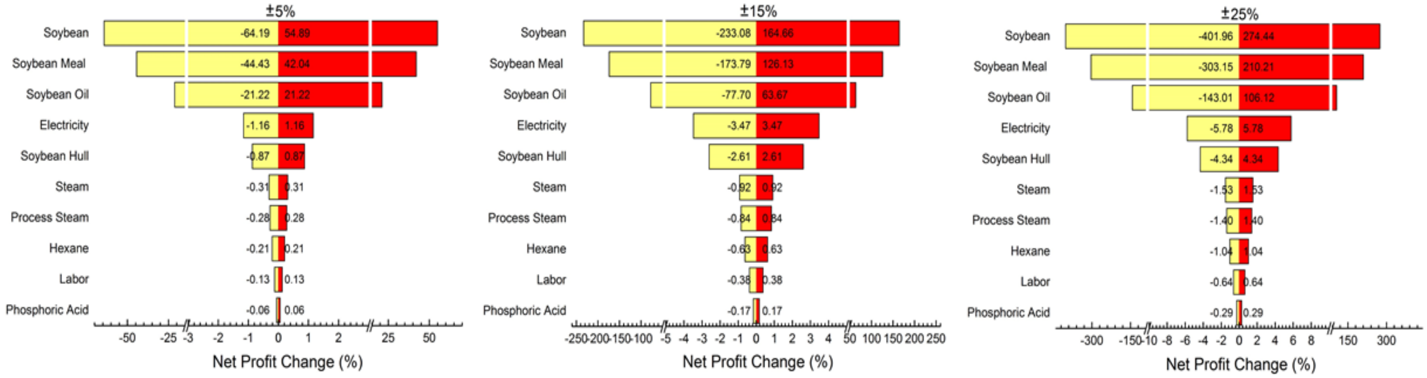
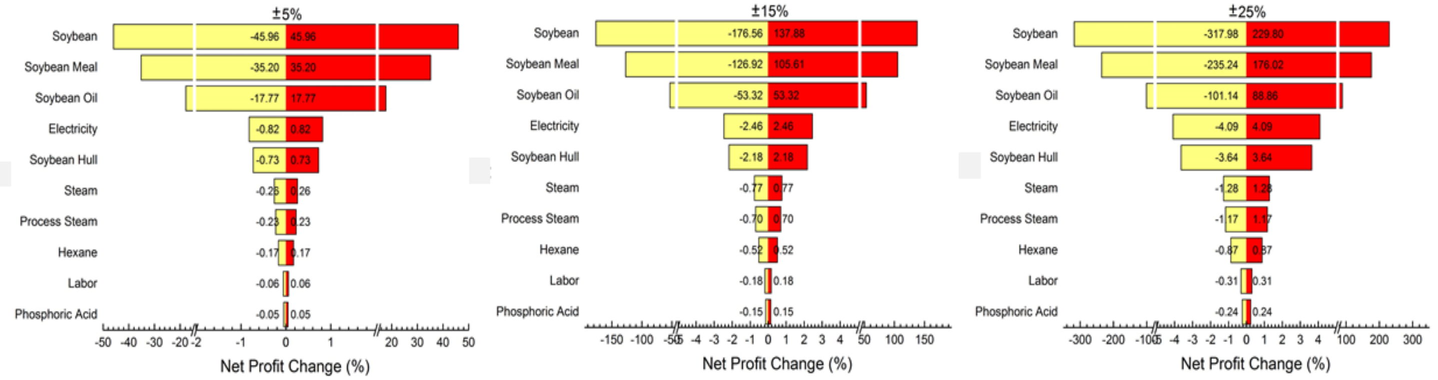


Fig. 7-2 Net profit changes with ±5%, ±15% and ±25% changes of operating costs and retailed prices of expelling process. The increase of operating costs shown in figure leads net profit to decrease and vice versa

(a) 86.61 million kg of annual soybean oil production



(b) 173.22 million kg of annual soybean oil production



(c) 415.73 million kg of annual soybean oil production

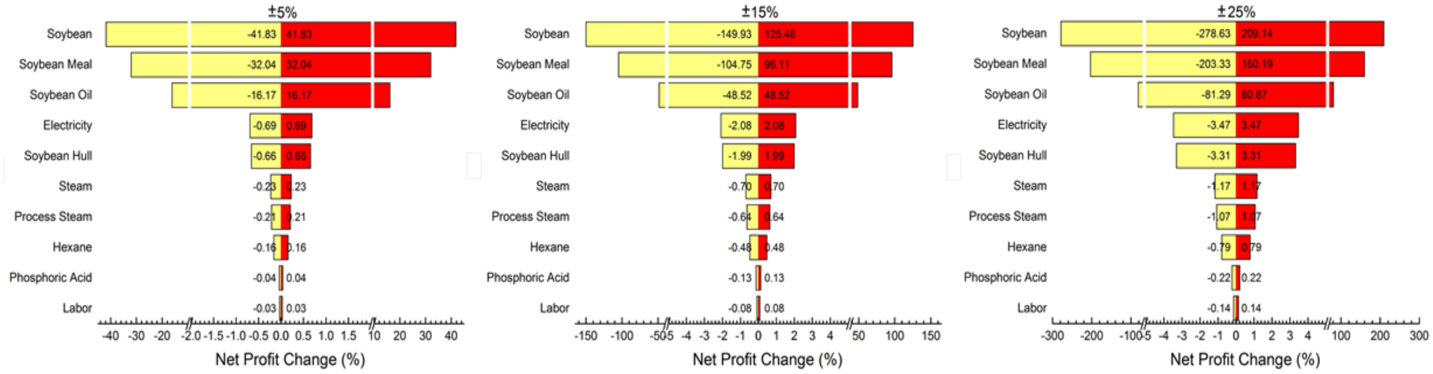
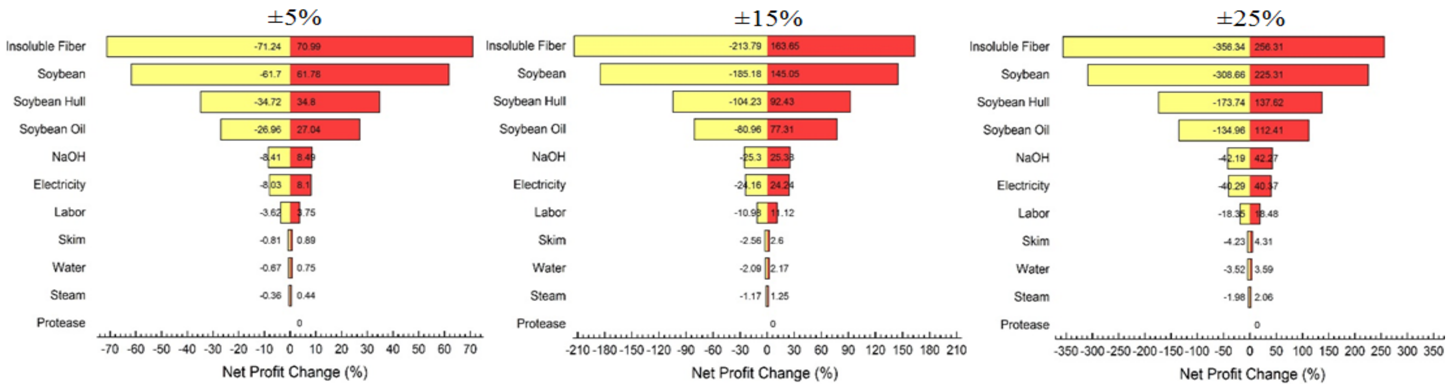
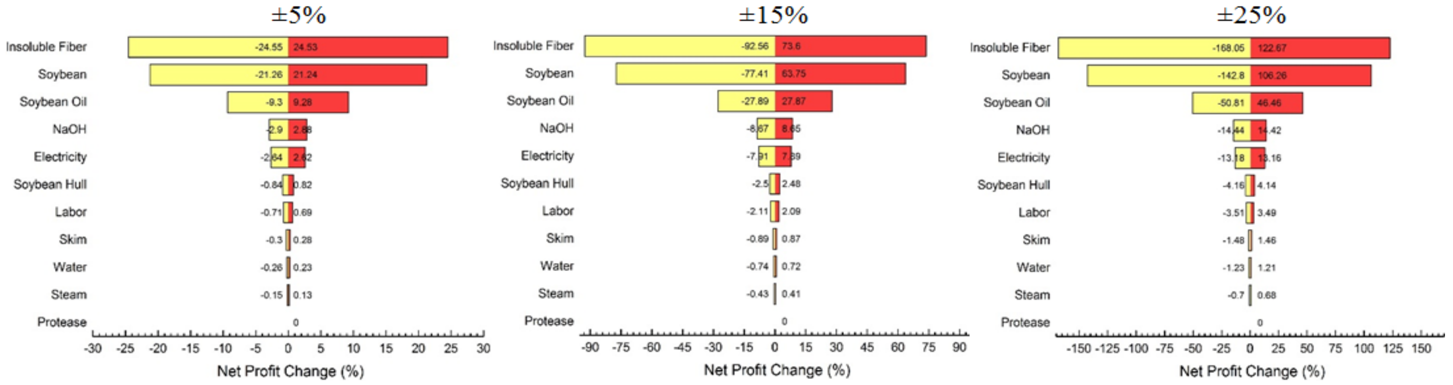


Fig. 7-3 Net profit changes with ±5%, ±15% and ±25% changes of operating costs and retailed prices of hexane extraction. The increase of operating costs shown in figure leads net profit to decrease and vice versa

(a) 8.475 million kg of annual soybean oil production



(b) 17 million kg of annual soybean oil production



(c) 51million kg of annual soybean oil production

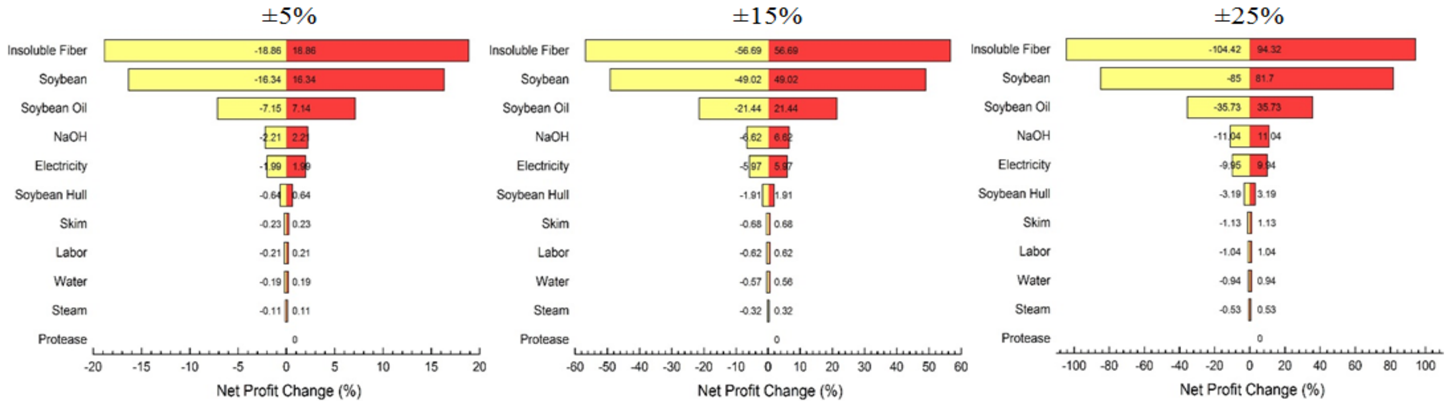


Fig. 7-4 Net profit changes with ±5%, ±15% and ±25% changes of operating costs and retailed prices of EAEP. The increase of operating costs shown in figure lead net profit decrease and vice versa

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CHAPTER 8

ENVIRONMENTAL IMPACT ASSESSMENT OF SOYBEAN OIL EXTRACTION PROCESSES

Modified from a paper to be submitted to the *Bioresource Technology*

Abstract

Expelling and hexane extraction are two typical processes for soybean oil production used in industry. The main issues for these two processes are the low efficiency and hazardous chemical problems respectively. Enzyme assisted aqueous extraction process (EAEP) was proposed to increase the efficiency without using organic solvent, which is replaced by water. The environmental impact analysis of these three processes are based on their mass flows, energy consumption and global warming potential. For mass flows, the environmental impact indices were calculated based on material flow of input and output components. Energy consumption was used to evaluate the carbon dioxide and other greenhouse gas (GHG) and criteria pollutants emissions by GREET models. According to the results, hexane extraction has the highest environmental impact due to the application of organic solvent. Expelling has the highest GHG and criteria pollutants emissions because of the high energy requirement for heat pressing processes. EAEP has similar environmental impacts to the expelling process, but it also lowers GHG and criteria pollutants emissions. EAEP has the potential to be a green process adopted by industry although a high energy intense pretreatment to produce finer soybean flakes for increasing oil recovery is still a challenge.

Keywords: Environmental impact, GHG emissions, Criteria pollutants, Expelling, Hexane extraction, Enzyme assisted aqueous extraction process (EAEP)

1. Introduction

The U.S. is the largest soybean producer in the world; around 33% of soybean production takes place in the America (SoyStats, 2015). Due to its high oil content (Bernardini, 1983), soybean is the main oilseed used in edible oil production. In industry, the mechanical pressing, expelling, and hexane extraction are two typically used processes. However, lower oil recovery from expelling, and safety and environmental issues (Li et al., 2004, Oliveira et al., 2013) resulted from hexane extraction are the main flaws in the soybean oil industry. For improving the oil yield and mitigating the safety and environment related problems caused by expelling and hexane extraction, the enzyme assisted aqueous extraction process (EAEP) has been developed and might be a proper method for industrial application (Rosenthal et al., 1996).

Before oil pressing and extraction, a series of pretreatment including cleaning, cracking, dehulling and conditioning is required (Fig. 8-1). These treatments are mainly used to clean crops and reduce particle size to increase the oil recovery (Lamsal et al., 2006). During the extraction step (Fig. 1), heat and pressing are applied in the expelling process to denature the oleosins and to break the structure of oil body to release oil. The solubility of hexane and oil is the principle for the solvent extraction to extract oil from crushed meal, and the desolvenization is applied to recover free oil and soybean meal. Further degumming and refining processes are needed for both expelling and hexane extraction to remove phospholipids and other impurities.

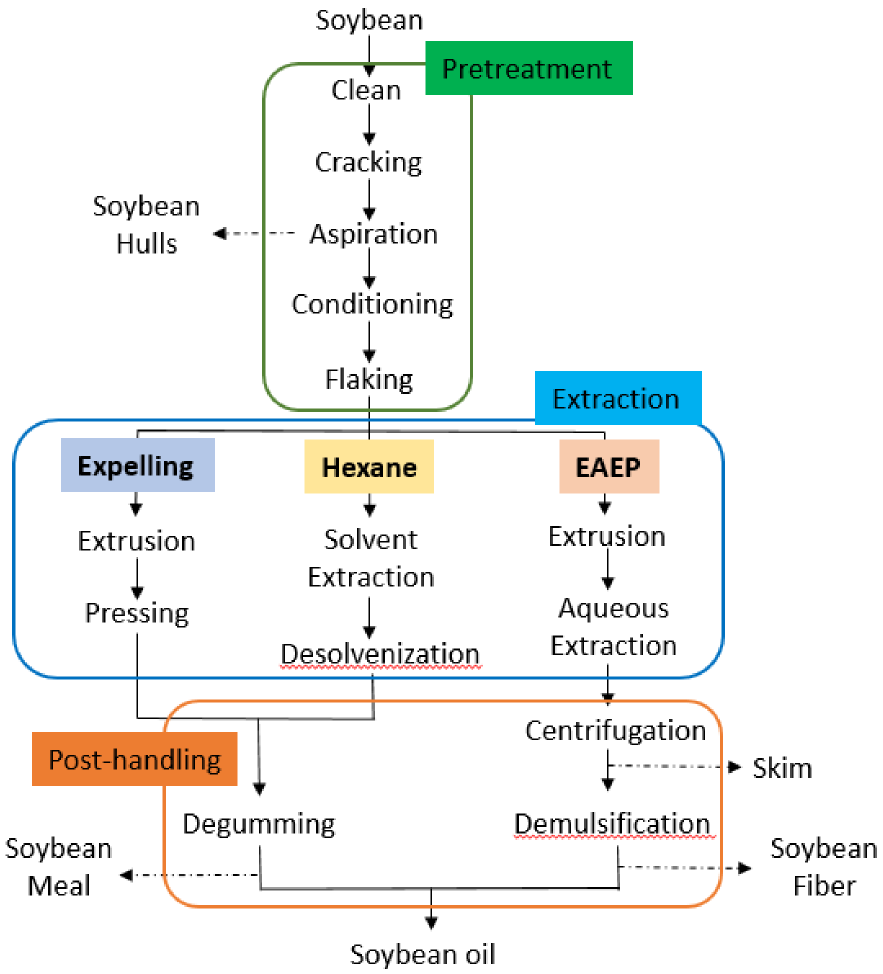


Fig. 8-1 Diagram of expelling process, solvent extraction and aqueous extraction of soybean oil production

As to aqueous extraction (Fig. 8-1), contrary to solvent hexane extraction, water is used as the solvent and the insolubility of water oil is applied. During the process, the oil in water emulsion is formed. Consequently, the demulsification is conducted to separate the oil from emulsion. The protein is extracted and dissolved in aqueous fraction as well; therefore, the further degumming process can be exempted (Johnson & Lucas, 1983, Jung et al., 2009, Sekhon et al., 2015). Thus, the safety and environmental related problems derived from chemical usages can be avoided. Additionally, this leads to a higher oil recovery than the mechanical pressing process.

In addition to technical improvement and feasibility, the environmental sustainability is another critical factor to evaluate the feasibility of the process. As to oil extraction, electricity is the main energy used in facility operations; steam is the heating resource which is mainly generated from a natural gas boiler built in the plant (Li et al., 2006). Besides energy consumption of the operation, the fossil-derived chemical addition is another critical issue for environmental impact evaluation especially for hexane extraction. For EAEP, water is used as the solvent which could mitigate the environmental impact when compared to solvent extraction. However, the demulsification has been regarded as a critical step for oil recovery in aqueous extraction due to its high energy requirement especially on physical (Hagenmaier et al., 1972, Harada & Yokomizi, 2000, McClements, 2005) and chemical methods (Menon & Wasan, 1985).

The environmental impact assessment (EIA) has been used to investigate the potential environmental impact resulted from the manufacturing. The mass balance, mass flow, and energy consumption are the main items used to evaluate the energy efficiency, and the greenhouse gas and pollutants emissions from the processes (Salomone & Ioppolo, 2012). Heinzle et al., (1998) proposed the quntifiying approach to evaluate the environmental impacts derived from chemical processing by calculating all input and outout components. Also, the Organization for Economic Co-operating and Development (OECD) proposed the environmental indicator to assess the sustainability of industrial processing in 2001.

There are many computation models which can be used for GHG and air pollutants emissions such as Aspen Plus (Morais et al., 2010) and Simapro (Kiwjaroun et al., 2009). The GREET model (the greenhouse gases, regulated emissions, and energy use in transportation model, Argonne National Laboratory) was introduced to evaluate the GHG and criteria air pollutants emissions. Although the GREET model has the restriction for only investigating biofuels used in transportation sector, the soybean oil has been regarded as a critical resource for biodiesel production. Therefore, the GHG and air pollutants emissions of soybean oil production can be extracted from the soy-based biodiesel GREET model (Huo et al., 2008). However, there were few studies manily focused on soybean oil production especially comparing different processes and the alternative extraction methodology.

This study mainly focuses on the comparison among these three extraction processes. The EIA is divided into two sections including environmental impacts derived from material flows of the process and the GHG and air pollutants emissions of oil extraction processes. Additionally, the environmental impacts will be quantified based on material balance of whole process especially for input and output components. The total energy consumption, heating agent and mass flow were used to build up an oil extraction pathway via the GREET model. The GHG and criteria air pollutants emissions were investigated by the GREET model. According to these criteria, the environmental feasibility among these three processes could be obtained and compared.

2. Materials and Methods

2.1 Boundary Definition

The boundary of soybean oil extraction includes oilseed pretreatment, extracting processes, oil refining and coproducts handling. The transportation however, was not considered (Fig. 8-2). Additionally, the land use and the generations of primary energies were not considered in this EIA. Steam (assumed to be produced by the boiler within the plant) and natural gas were used as the primary source for heat energy. Therefore, the whole boundary can be seen as the producing plant.

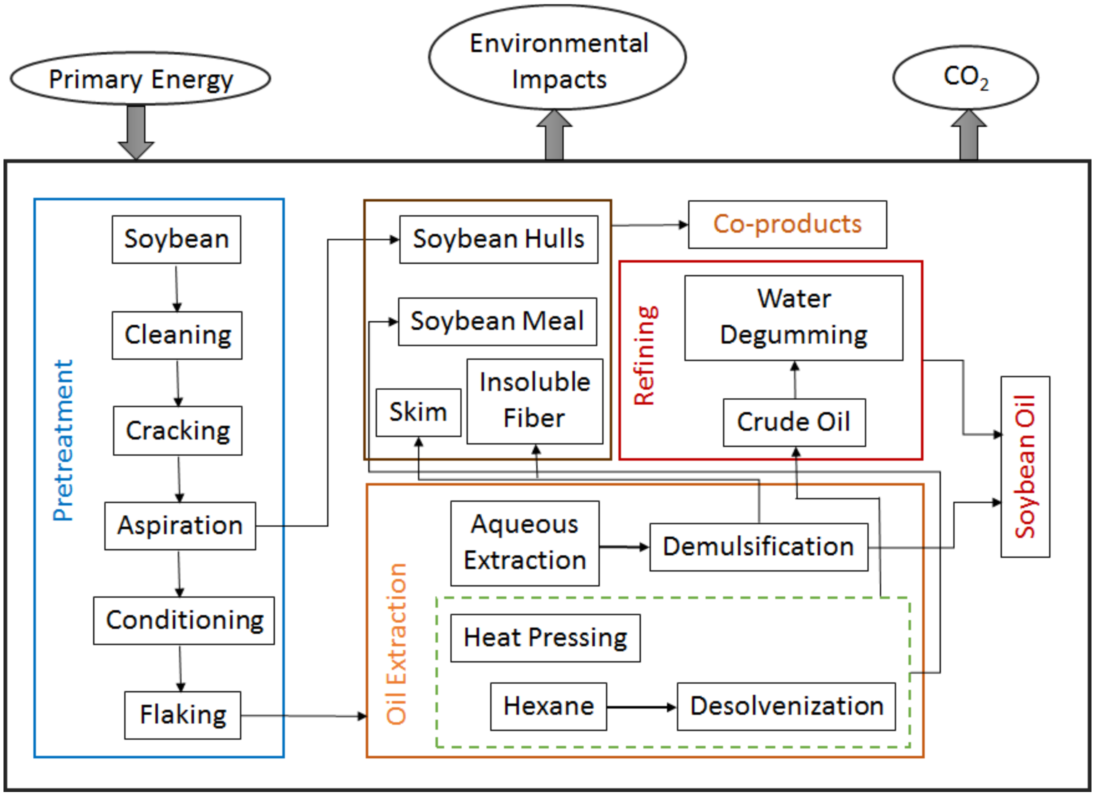


Fig. 8-2 Boundary of soybean oil extraction environmental impact assessment

2.2 Environmental Impact

Material flow is the main factor for evaluating the environmental impact. The material flow is separated into input and output components. The data of expelling and hexane extraction were collected according to the biodiesel simulation model built by Haas et al., (2006); and the EAEP was evaluated based on de Moura's research (2011). The mass flow of input components, output components and the mainproduct are shown in Table 8-1, and they are the basis for the further environmental indices calculations.

Table 8-1 The mass flow of input and output components

Components	Input/Output (I/O)	Mass flow (kg/hr) by each process		
		Expelling	Hexane	EAEP
Soybean	I	24278.18	24278.18	12423.54
Hexane	I	N/A	21755.69	N/A
Water	I	1787	3068.63	59895
NaOH	I	N/A	N/A	67
H_3PO_4	I	8	17.50	N/A
Protex 6L	I	N/A	N/A	106.5
Solid Wasted	O	72.84	72.49	1644.23
Water	O	2156.31	1944.96	N/A
Sewage	O	412.70	1347.34	N/A
Hexane	O	N/A	22291.84	N/A
NaOH(aq)	O	N/A	N/A	4818.28
H_3PO_4(aq)	O	193.22	188.01	N/A
Soybean Hulls	O	N/A	801.39	733.55
Soybean Meal	O	20003.09	18100.22	N/A
Skim	O	N/A	N/A	54689.17
Insoluble Fiber	O	N/A	N/A	8358.32
Protex 6L	O	N/A	N/A	106.5
Soybean Oil	Main Product	3235.02	4374.24	2141.99

2.2.1 Component Classification

For the environmental impacts, the material flow was divided into input and output components, and there are four impact groups for each component individually. Also, there are several categories which are set up for each impact group (Heinzle et al., 2006). The hierarchical diagram of EIA is shown in Fig. 8-3.

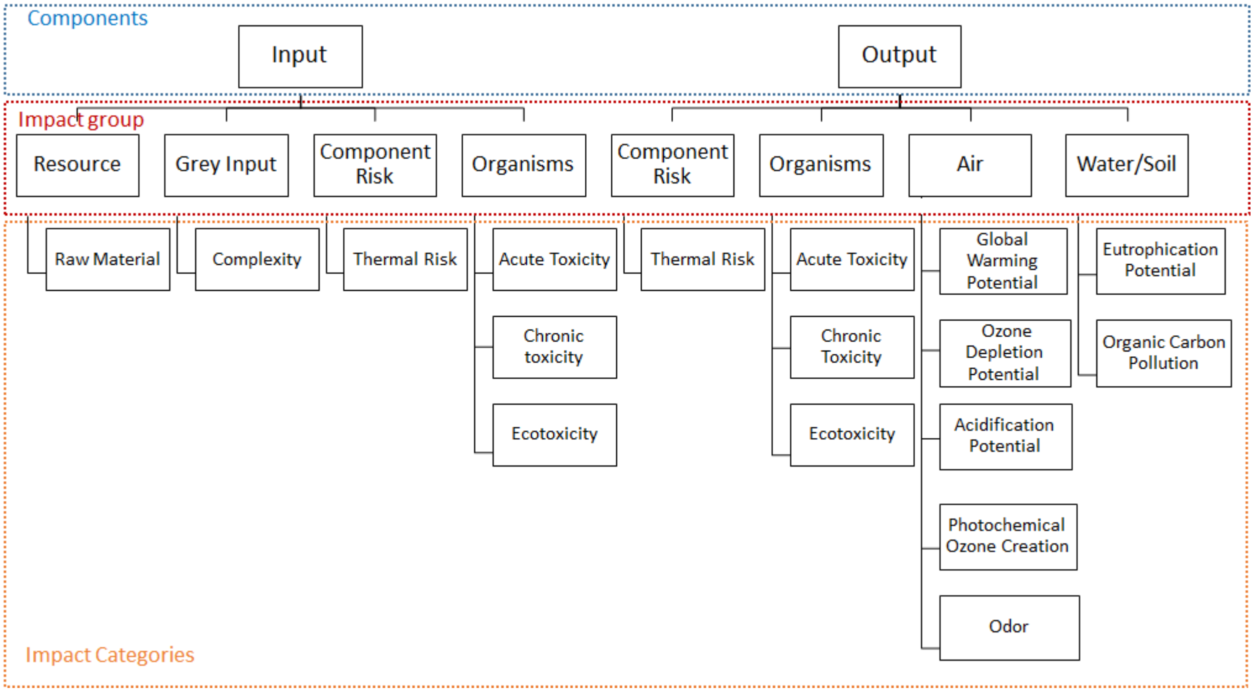


Fig. 8-3 Hierarchy of environmental components and impacts

As the hierarchy of environmental components shows, impact groups and categories are built and the impcat categories are allocated into three classifications (A, B and C) based on the level of potential risk and toxicity of a component in the process (Table 8-2). The highest class in the referred impcat cataegories defines the classsification of the impact category for each impact group.

Table 8-2 Criteria for impact category classification

Impact Category	Class A	Class B	Class C
Raw Material Availability	Fossil derived, exhaustion with 30 years	Fossil derived, exhaustion with 30-100 years	Exclusively renewable or long term supply
Critical Material Used	Heavy metal, AOX, PCB used or produced in stoichiometric amounts	Involved in sub-stoichiometric amounts	No critical components involved
Complexity of Process	>10 stages	3-10 stages	<3 stages
Thermal Risk	R 1-4, 9, 12, 15-17, 44; EU: F^+, E; NFPA F+R: 3, 4.	R 5-8, 10, 11, 14, 18, 19, 30; EU: F, O; NFPA F+R: 2	NFPA F+R: 0, 1
Acute Toxicity	EU: T^+; R 26-28, 32; CH-poison class: 1, 2; NFPA H:4; WGK 3; ERPG: <100 mg/m^3 ; IDLH : <100 mg/m^3	EU: T, X_n, X_i, C; R 20-25, 29, 31, 34-39, 41-43, 65-67; CH-poison class: 3, 4; NFPA H: 2, 3; WGK 2, ERPG: 100-1000 mg/m^3 ; IDLH: 100-1000 mg/m^3	CH-poison class: 5; NFPA H: 0, 1; WGK 1; ERPG: >1000 mg/m^3; IDLH: >1000 mg/m^3
Chronic Toxicity	MAK: <1 mg/m^3; IARC: 1, 2A; R 45-49, 60-61, 64	MAK : 1-10 mg/m^3 ; IARC : 2B, 3 ; R 33, 40, 62, 63 ; EU : T, T^+, X_n ; CH-poison class : 1, 2	MAK : >10 mg/m^3; IARC: 4; CH-poison class: 3, 4, 5
Ecotoxicity	EU: N; R 50; WGK 3	R 51-58; WGK 2	WGK 1 or no water hazard
GWP	>20	<20	N/A
ODP	>0.5	<0.5	N/A
AP	>0.5	<0.5	N/A
POCP	>30 or NO_x	2-30	<2 or no effect
Odor		Threshold < 300 mg/m^3	Threshold >300 mg/m^3
EP	N-content>0.2 or P-content>0.05	N-content < 0.2and P-content < 0.05	No N and P
OCPP		ThOD>0.2g O_2/g substrate	ThOD<0.2 g O_2/g substrate or no organic compound

GWP: global warming potential; ODP: ozone depletion potential; AP: acidification potential; POCP: photochemical ozone creation potential; EP: eutrophication potential; OCPP: organic carbon pollution potential

In impact category classification, critical chemical and complexity were evaluated based on Ullmann's Encyclopedia of Industrial Chemistry (Ullmann, 1985); thermal risk and acute toxicity are reffered to the study of Budavaris et al., (1989). And these categories are also evaluated according to R-phrase, EU classification, standard system for the identification of the hazards of materials for emergency respond established by National Fire Protection Association (NFPA), CH-poison classification, German water hazard class (WGK), emergency response planning guideline (ERGP) and immediately dangerous to life or health value (IDHL) established by US National institute for Occupational Safety and Health (NIOSH).

Additionally, the air and water/soil impact groups were evaluated based on their eutrophication potential and organic carbon pollution potential (Houghton, et al., 2001, UNEP, 2000, Derwent et al., 1998, Heijungs et al.,1992).

2.2.2 Environmental Impact Indices

According to the material flow and mass balance, the mass index (m_i) of each input and output component are calculated first which is defined as the ratio of input/output component to the main product (soybean oil, m_p). After obtaining the mi of each component, the mass index of total input ($MI_{p,\ in}$) and output components ($MI_{p,\ out}$) of the process can be calculated by following Eq. 1 and Eq. 2. The $MI_{p,\ out}$ was less than $MI_{p,\ in}$ by 1 because the main product was not considered in the total MI of output process.

$$MI_p, in = \sum_{1}^{i} \frac{m_i}{m_p} \qquad Eq. 1$$

$$MI_p, out = \sum_{1}^{i} \frac{m_i}{m_p} - 1 \qquad Eq. 2$$

Based on the classification of each impact category derived from the input/output components, there are two quantifying systems, multiplying and averaging, used for the assessment. First of all, these three classifications are converted into the values which are the multipliers for the environmental indices calculation. For the multiplying system (Eq. 3), classes A, B and C are referred to values of 4, 1.3, and 1 individually. The values of 1, 0.3, and 0 are used in the averaging system (Eq. 4) for these three classes respectively. These values were the basis for the calculation of environmental factors (EF). Due to the 4 impact groups of input and output components, the EF for these components are 1-256 and 0-4 for EF_{multi} and EF_{mv} respectively (Heinzle et al., 2006).

$$EF_{multi} = \prod_{1}^{j} G_j \qquad Eq.3$$

$$EF_{mv} = \frac{G_1 + G_2 + G_3 + G_4}{j} \qquad Eq.4$$

Furthermore, the environmental impact (EI) is defined as the multiplication of EF and m_i for each component (Eq. 5), and the summation of each component EI is defined as the total process environmental index denoted as EI_p (Eq. 6). Consequently, the general effect impact (GEI) was calculated as the ratio of EI_p to MI_p (Eq. 7) (Heinzle, et al., 1998).

$$EI_i = EF_i \times m_i \qquad Eq.5$$

$$EI_p = \sum_{1}^{i} EI_i \qquad Eq.6$$

$$GEI = \frac{EI_p}{MI_p} \qquad Eq.7$$

2.3 GHG and Criteria Air Pollutants Emissions

Based on the expelling, hexane extraction, and EAEP (refers to Chapter 3-5), electricity was the main energy resource for powering the facility and steam was used as the heating agent in the process. The total energy consumption was simulated and calculated by SuperPro Designer v9.0 (Intelligen, Inc., Scotch Plains, NJ).

The GHG emissions, including CO_2, N_2O, CH_4, and other criteria air pollutants emissions such as CO, volatile organic compound (VOC), nitrogen oxide (NOx), sulfur oxide (SOx), PM10, PM2.5, and black carbon (BC) are estimated via the GREET model (Argonne National Lab, 2015).

The electricity is set according to Iowa's electric profile (Iowa Utilities Board, 2015). It is generated from coal (52.61%), wind (31.57%), natural gas (4.23%), petroleum (0.19%), nuclear (9.25%), hydropower (1.69%), and other renewables (0.46%). The steam is produced by a natural gas boiler built in the plant. The electricity and steam consumption for producing 1 kg soybean oil are listed in Table 8-3.

Table 8-3 Energy requirements for 1kg soybean oil production

Processes	Steam (t)	Electricity (kwh)
Expelling	0.01	6.22
Hexane	1.82	1.02
EAEP	1.00	4.44

3. Results and Discussions

3.1 **Input Components**

3.1.1 Classification of Impact Groups and Categories

The results according to the classification of the impact groups and categories for input components are shown in Table 8-4. In the resource group, these three processes are allocated to class B due to the addition of chemicals, namely the hexane which is used in solvent extraction. Though only small amounts of phosphoric acid were used in the degumming process for expelling and hexane extraction it still is seemed as a critical chemical input for the process. NaOH was used in EAEP for pH adjustment which is the critical material input for EAEP. For grey input, all processes were undergoing oilseeds pretreatment, extraction, degumming/demulsification and coproducts handling at least 3 steps. Therefore, they all belonged to class B.

Table 8-4 Classification of impact groups and categories for input components

Impact Group	Impact Category	Expelling	Hexane	EAEP
Resources	Raw materials	C	C	C
	Critical materials	B	B	B
Grey input	Complexity	B	B	B
Component risk	Thermal risk	C	B	C
Organism	Acute toxicity	B	B	B
	Chronic toxicity	C	A	C
	Ecotoxicity	C	B	C

In regards to risk, hexane was used for solvent extraction which is allocated to class B. Based on hazard profile, hexane has thermal risk, hence it was assigned to Class B and expelling and EAEP were in Class C. As to the organisms group, hexane also has acute toxicity and ecotoxicity due to its R-phrase of 11, 20, 51, 53, 65 and 67, and NFPA F:3 which were allocated to class B. However, it also has class A of chronical toxicity due to the R-phrase of 48 (Hexane, 2016), therefore the organisms group of hexane extraction was assinged to Class A. As for EAEP, owing to the application of NaOH, which was used to adjust the pH during the extraction, it led to acute toxicity and was allocated to Class B due to its R-phrase of 35 (Sodium Hydroxide, 2016). For the expelling process, phosphoric acid is the only chemical used in the operation, however it also has Class B of acute toxicity due to the R-phrase of 34 (Phosphoric acid, 2016). Therefore, expelling and EAEP were assigned to Class B for the organisms group.

3.1.2 Environmental Impact Indices of Input Components

According to the mass index of each component, the results (Fig. 8-4) reflect the material flow of each process. Again, expelling only used small amounts of phosphoric acid in the dugumming process; hexane was used in the extraction and EAEP used large amounts of water as the solvent for the extraction. Hence, EAEP has the highest mass index among these three processes. Additionally, hexane has the highest oil recovery which can be observed from the MI results below (specifically the Soybean measurements).

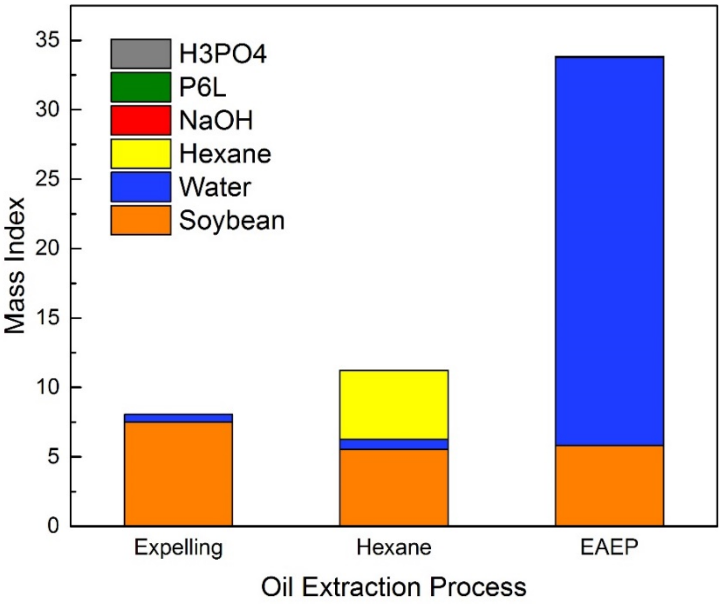
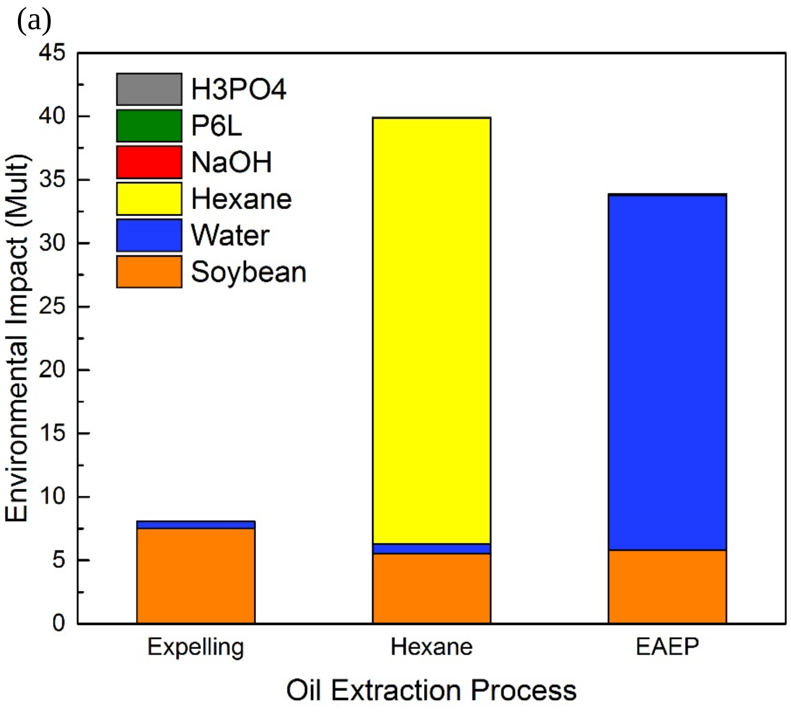


Figure 8-4. Mass index of input components

Based on the calculations of EFs and MIs, two systems (multiplying and averaging) were conducted (Fig. 5). From the results, hexane extraction has the highest EI in both assessment systems, and the EI is mainly from hexane due to its high environmental risk potential. Thus, hexane is seen as the “Hot Spot” of the hexane extraction. However, as these two assessment systems were compared, the components without environmental impacts were also considered for the multiplying system. For averaging system, it only calculated the components with thermal and organism risks. These conditions can be observed from the quantification of the different classes of impact categories. Thus, from the results of EI of the averaging system, the components with environmental impact potential are more easily observed. As for the expelling process and EAEP, H_3PO_4 and NaOH have environmental risk potential. Therefore, they are the “Hot Spots” of these two processes individually. In the aspect of enzyme (P6L) used in EAEP, the bio-derived enzyme also gives to EI due to its producing processes and nitrogen and sulfur contents.



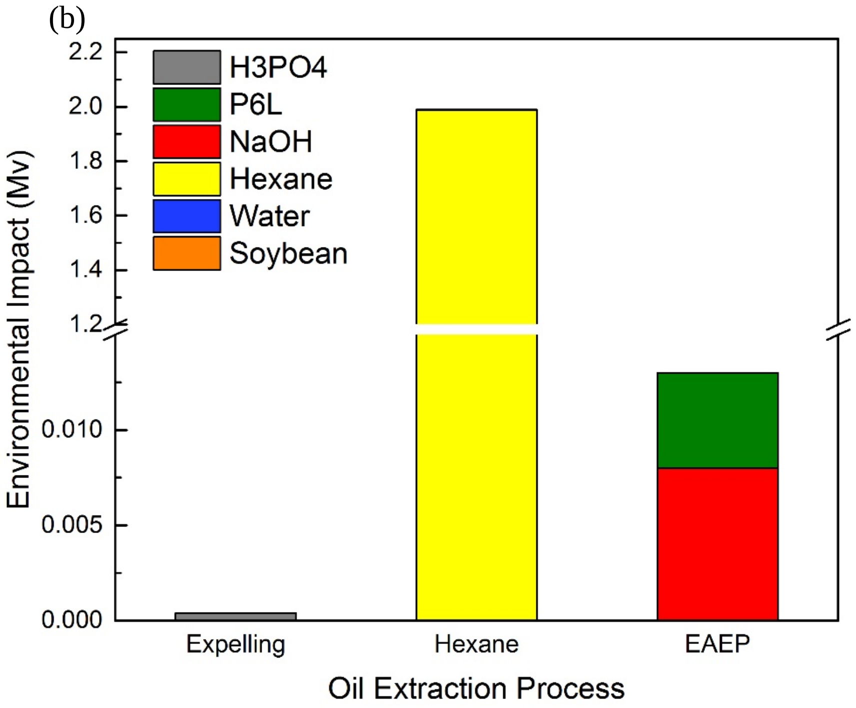


Fig. 8-5 Environmental impact of input components. (a) multiplying system; (b) averaging system

GEI can be estimated by $EI_{p,\ in}$ and $MI_{p,\ in}$, and that is the general index for evaluating the environmental impact potential for the whole process. According to the results (Fig. 8-6), the hexane extraction process has the highest general impact potential because hexane gives the highest score of the environmental indices among all input components. For EAEP, it has almost the same impact potential as expelling, however, the significant difference can be observed from the averaging system. In the averaging system, the expelling process has the lowest GEI because H_3PO_4 is the only component giving the environmental impact for the process. Additionally, this trend can be also observed from the results of $EI_{p,\ in}$.

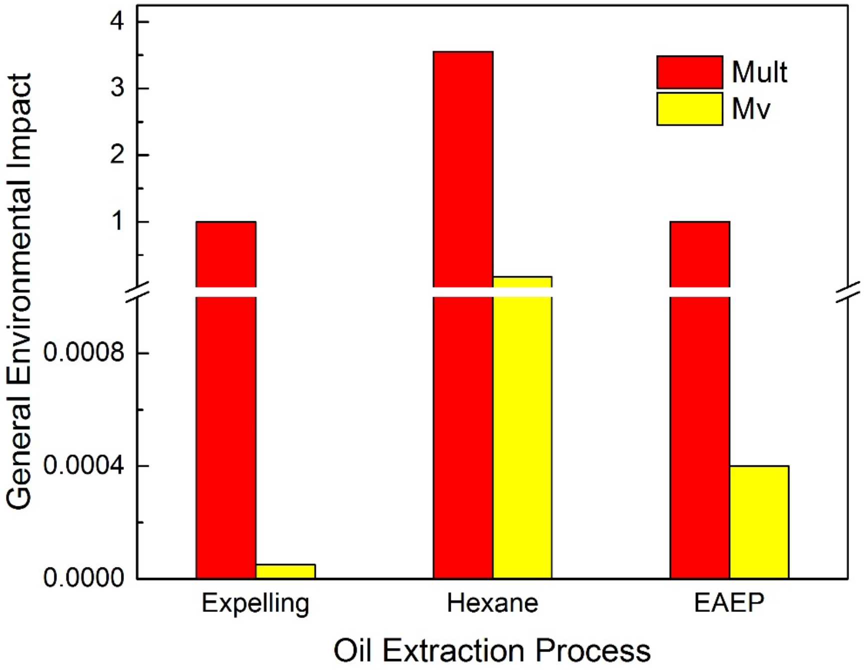


Fig. 8-6 General environmental impacts of input components

3.2 Output Components

3.2.1Classification of Impact Groups and Categories

The classification of impact categories for output components is shown in Table 8-5. In the component risk and organisms groups, the results are similar to the input components. The hexane emitted from the solvent extraction and evaporated from desolvenization leading the organisms group of hexane extraction to be assigned to Class A. The organisms group of the expelling process and EAEP was allocated to Class B because there was wasted NaOH present in EAEP and the wasted H_3PO_4 from the expelling process.

Table 8-5 Classification of impact groups and categories for output components

Impact Group	Impact Category	Expelling	Hexane	EAEP
Component risk	Thermal risks	C	B	C
Organisms	Acute toxicity	B	B	B
	Chronic toxicity	C	A	C
	Ecotoxicity	C	B	C
Air	Global warming potential	C	C	C
	Ozone depletion potential	C	C	C
	Acidification potential	C	C	C
	Photochemical potential	C	C	C
	Odor	C	C	C
Water/Soil	Eutrophication potential	B	B	B
	Organic carbon pollution	B	B	B

Hexane however, has no GWP, ODP, AP, or POCP (TRACI 2.1, 2014). Also, the NaOH solution used in EAEP and H_3PO_4 applied for degumming in the expelling and hexane extraction had the same results as solvent extraction for the air impact group. In the water/soil group, all processes produced solid wastes; sewage which consists of protein, carbohydrates, and lipids. Therefore, they all had environmental impacts potential and were allocated into class B.

3.2.2 Environmental Impact Indices of Output Components

According to the products, co-products and wastes produced from each process, the mass index of the output components are shown in Fig. 8-7. Soybean meal is the main co-product of the expelling and hexane extraction, however, the hexane is still the critical factor for solvent extraction even though the countercurrent and continuous system was used to reduce the total amount.

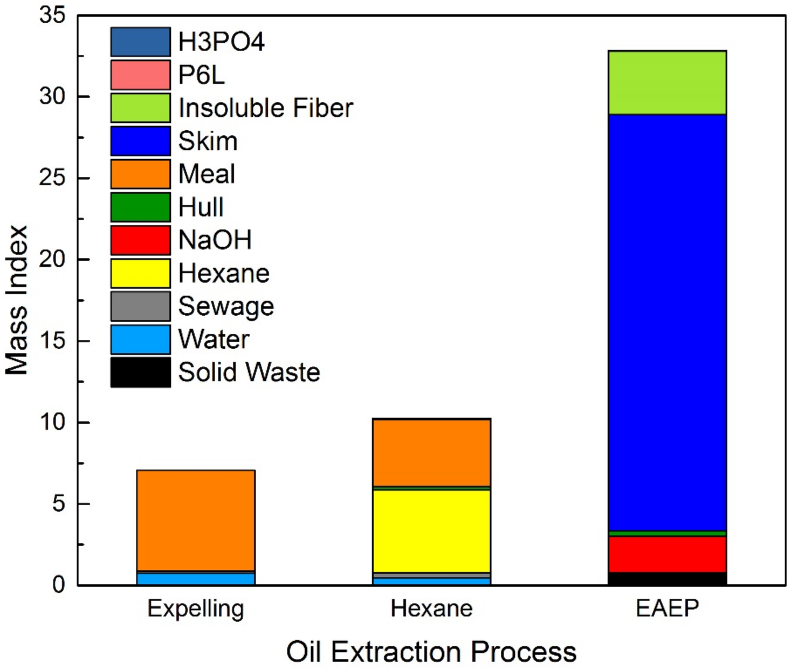
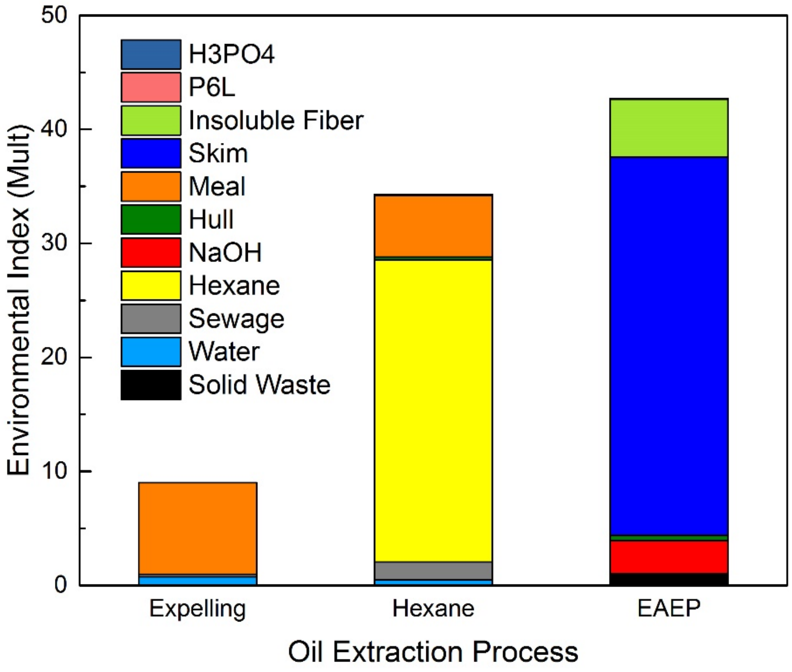


Fig. 8-7. Mass index of output components

For EAEP, the skim was produced from the extraction, and the highest mi of the skim indicated that large amounts of water were needed for the aqueous extraction to form the oil in water emulsion. Additionally, the insoluble fiber and NaOH were two other critical components for EAEP. These results also indicate the proper strategy for the co-product and waste handling that is essential for EAEP to decrease its final environmental impacts due to its high $MI_{p,\ out}$. Therefore, the skim and insoluble fiber were proposed to be applied as another material for corn-based ethanol production in the corn-soybean integrated biorefinery system. Otherwise, these co-products were claimed to increase the ethanol yield in corn-based bioethanol production with synergetic effect, and that would also increase the potent application of EAEP in industry (Sekhon et al., 2015).

The results of $EI_{p,\ out}$ from the multiplying and averaging systems are illustrated in Fig. 8. From the results, the EAEP has the highest EI in both systems, and the skim is the “Hot Spot” for the output components because large amounts of water were applied during extraction which resulted in plenty of skim fraction being collected from the centrifugation. Hexane is still the Hot Spot of hexane extraction output components which remained in sewage and was collected from vapor during the desolvenization. For the expelling process, the co-products, soybean meal is main resources of EI. Additionally, the H_3PO_4 remained in the wasted water after degumming process also played a critical role in environmental impact which can be observed from averaging system (Fig. 8b).

(a)



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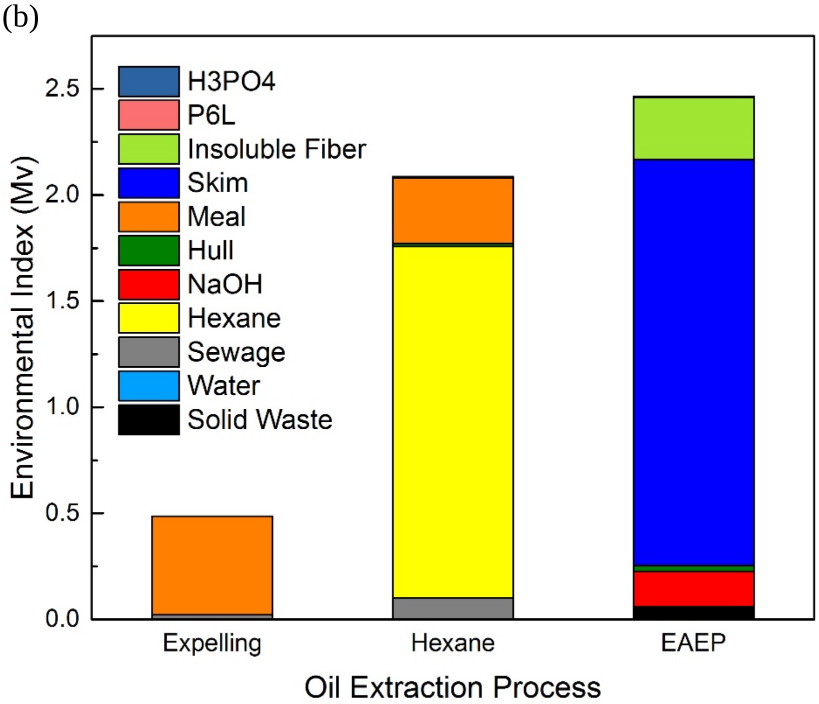

Fig. 8-8. Environmental impact of output components. (a) multiplying system; (b) averaging system

From the perspective of general environmental impact (Fig. 8-9), hexane extraction still gives the highest general impact potential although it has the lower EI. The presence of hexane in the extraction process has higher component and organism risks, and these factors lead to the higher final scores in the GEI. For the EAEP and the expelling processes, the result trend is similar to input components. The results from both the multiplying and averaging systems are much closer than input components because the co-product was included in the assessment. Therefore, from the results of input and output components, the expelling process has the lowest environmental impact potential because of the least amounts of chemical additives in the degumming process; the EAEP could mitigate the environmental impact potential by substituting hexane with water as the extracting agent.

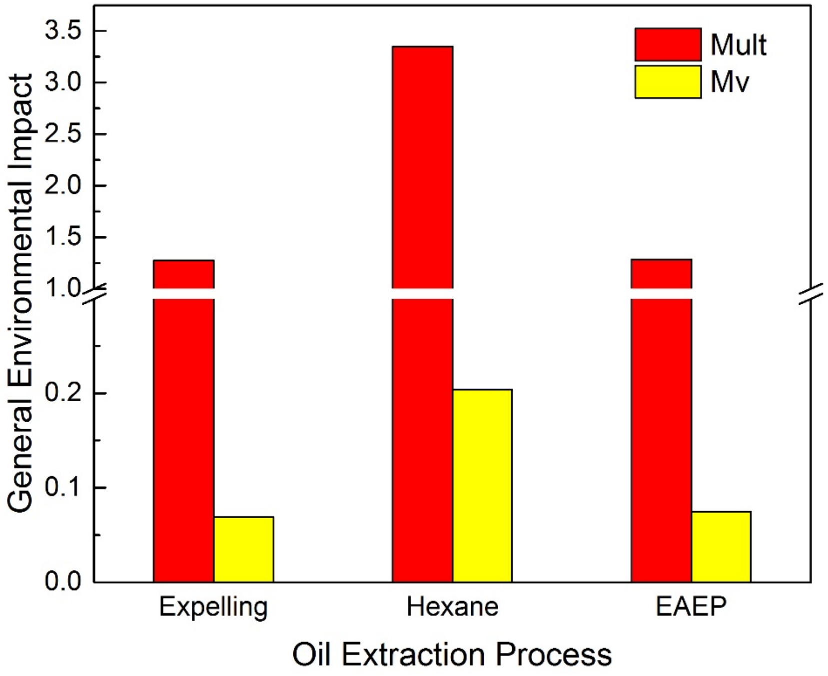

Fig. 8-9. General environmental impacts of output components

3.3 Energy Consumptions

According to the soybean oil annual production, electricity and steam were the main energy resources for the operation. Electricity was used to power the facilities in the plant; and, steam was the heating agent mainly used in drying and the desolvenization processes.

The whole extraction process was divided into three main steps including pretreatment, extraction, and post handling. The electricity allocation of these three main steps are illustrated in Fig. 8-10. According to the results, extraction takes over 95% for the expelling process whereas pretreatment and extraction take about 65% and 27% for hexane extraction individually. EAEP has over 90% of electricity consumption for the pretreatment. These results indicate that extruding and heat pressing cost a lot of energy for the expelling process, however, hexane extraction requires sufficient pretreatment to increase soy meal surface area for achieving high efficiency during the extraction step. EAEP has a higher pretreatment requirement than hexane extraction because cracking, flaking, and extrusion were used to break down the cell wall structure to improve the formation of oil in water emulsion (Jung et al., 2009). Therefore, the higher electricity requirement for pretreatment can be observed. Otherwise, the hexane process has the highest electricity consumption in posthandling among these three processes because desolvenization is a critical step to revome residual hexane in the soybean oil and meal.

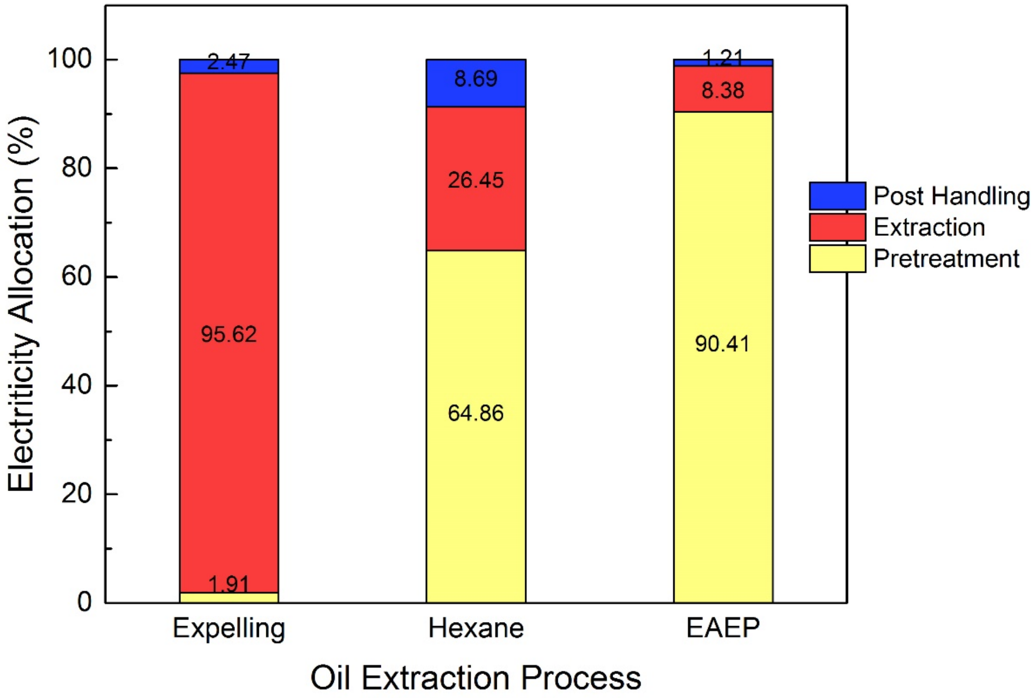

Fig. 8-10. Electricity consumption for oil extraction processes

These results also reflect that expelling has lower oil extraction efficiency and the solvent extraction needs more energy for post handling indicating the requirement for desolvenization. On the contrary, the EAEP has the lowest electricity in post handling because it’s able to separate oil and protein simultaneously and there is no meal production during the process.

3.4 GHG and Criteria Air Pollutants Emissions

According to the primary energy consumptions of these three oil extraction processes, the GHG emission were evaluated based on 1 kg of soybean oil production by the GREET model, and the results are shown in Fig. 8-11.

GHG includes CO_2, CH_4 and N_2O mainly, and they are emitted via burning fossil fuels. Additionally, agricultural and industrial activities are able to emit GHG, especially CH_4 and N_2O from burning biomass and municipal solid wastes, landfills, and fertilizer handling (EPA, 2014). Besides GHG emissions, other criteria pollutants which result in global warming effects indirectly such as CO and NO_x. Otherwise, some pollutants cause impact to human health such as SO_x, particulate matters (PM_{10}, $PM_{2.5}$), volatile organic compounds (VOC), precursor organic compounds (POC), and black carbon (BC) which are also generated from the combustion of fossil fuel for electricity generation and industrial activities.

From the results, CO_2 is the major GHG emission followed by CH_4. SO_x is the main criteria air pollutant emitted from the soybean oil extraction. In this study, Iowa’s electricity generation mix was applied, and around 58% of electricity is generated from fossil fuels (about 53% from burning coal). Therefore, CO_2, CH_4 and SO_x take the major GHG and pollutants emissions.

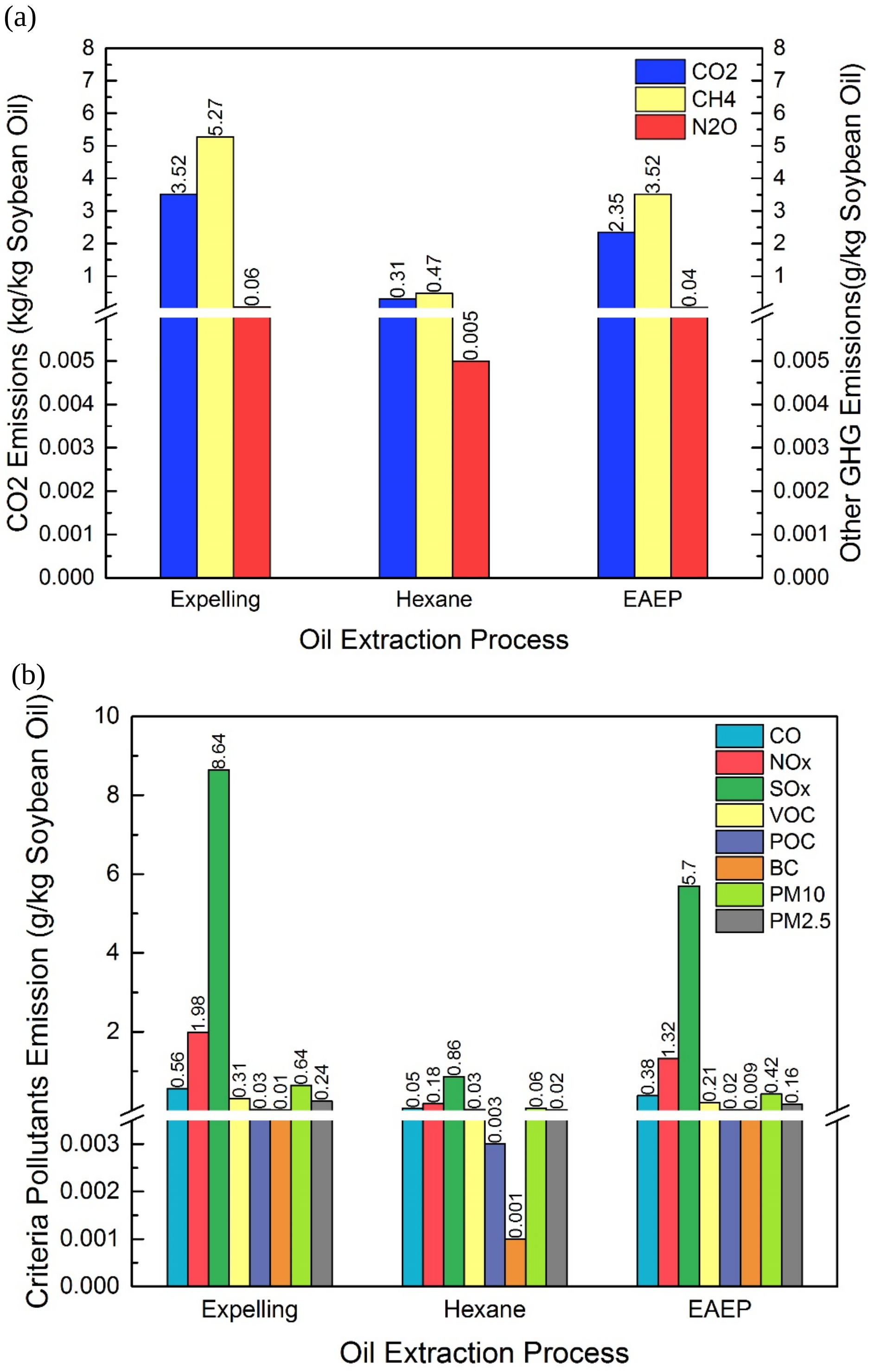

Fig. 8-11. GHG and criteria pollutants emissions of oil extraction processes. (a) GHG emissions; (b) criteria pollutants emissions

Among these three oil extraction processes, hexane extraction has the lowest GHG emissions about 0.31kg CO_2 and 0.47g CH_4 emitted per 1 kg of soybean oil production (Fig. 8-11a). This indicates that hexane extraction is the most energy efficient approach for oil extraction although large amounts of steam are required for desolvenization. Therefore, that could be the reason to explain why solvent extraction is the most common method used in industry. For the expelling process, the intense energy requirement for the pressing is the main reason to have the highest GHG emissions (3.52kg CO_2 and 5.27g CH_4 per 1kg of soybean oil production). Additionally, the results reflect that expelling has lower oil recovery than solvent extraction, and that is the main disadvantage of the mechanical process (Li et al., 2004). As to EAEP, the electricity consumption in pretreatments is the driving force to lead to the higher GHG emssions than from hexane extraction. The finer the soybean flakes were produced, the more oil recovery efficiecy was obtained. Although the enzyme was used to assist the demulsification which could reduce the energy consumption at some level (Lamsal et al., 2006, Jung et al., 2009), the amount of energy consumption reduced by applying enzyme has limited ability to leverage the energy consumptions in pretreatment. However, it has lower GHG emissions (2.35kg CO_2, 3.52g CH_4 and 0.04g N_2O per 1kg of soybean oil production) than the expelling process. This result indicates EAEP still has the potential to be applied in industry which could increase oil recovery and mitigate GHG emissions by about 33% compared to the typical expelling process.

In criteria air pollutants emissions, the trend is similar to GHG emissions. The expelling process still has the highest criteria pollutants emissions among these three processes. Hexane extraction has the lowest criteria pollutants emissions (Fig. 8-11b). For EAEP, the criteria pollutants emissions is reduced by about 34% compared to the expelling process. Hence, we could conclude that the hexane extraction is the highest energy effcient process and EAEP could be the alternative process used in industry because it increases oil recovery and mitigates GHG and criteria pollutants emissions better than the typical expelling process.

4. Conclusions

From the results of environmental impacts, energy consumptions, GHG and criteria pollutants emissions, this proves that expelling is a clean approach for oil extraction with the lowest environmental impacts, but it generates the highest GHG and criteria pollutants emissions due to high energy intense heat pressing process. However, although hexane extraction is the most energy efficient and has the lowest GHG and criteria pollutants emissions, it has the highest environmental impact potential due to the application of organic solvent. For EAEP, it has been seen as an alternative to reduce the environmental impacts and also to maintain the high oil recovery. Obviously, the EAEP has the lower environmental impacts and the GEI values than hexane extraction which are quite close to the expelling process. Also, it has lower GHG and criteria pollutants emissions than the expelling process though higher energy consumption is required to produce finer soybean flakes to improve oil recovery. Conclusively, EAEP has the potential to be a green process because it could have a lower environmental impact than hexane extraction and reduce total energy consumption leading to lower GHG and criteria pollutants emissions than the expelling process. Additionally, there is still a challenge for EAEP to lower energy requirements in pretreatment to meet lower GHG and criteria pollutants emissions.

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CHAPTER 9

FRACTIONATION OF DISTILLERS DRIED GRAINS WITH SOLUBLES (DDGS) BY COMBINATION OF SIEVING AND ASPIRATION

Modified from a paper published in the *Food and Bioproduct Processing*

Abstract

Distiller's dried grains with solubles (DDGS) is a coproduct of corn-based ethanol industry and it is a good resource of protein and oil for animal feeds. High protein and oil content DDGS is desired because of its high nutritional and economic values. Physical separation is an easy approach to increase oil and fat content based on profiles of components. Protein and oil rich DDGS tends to exist in finer particle; fibers rich DDGS is observed in large particle fraction. A primary sieving connected with aspiration fraction is used to condense protein and oil contents for DDGS. Particle size, air flowrate and different fractions derived by aspiration are independent variables. The proper combination and interaction of variables for protein and oil separation are higher flowrate, smaller particle sizes, and the heavy fraction. And, the best efficiency for protein and oil separation reaches about 29.7 and 68.15% respectively. For fiber separation, a mild condition results in higher fiber content approximately 7%. Additionally, the relationship between nutrient separation and independent variables can be expressed by a linear model. The combination of primary sieving and aspiration with specific air flowrate used in fractionation process can increase value to corn-based ethanol industry.

Keywords: DDGS, Fractionation, Sieving, Aspiration, Nutrients

1. Introduction

Distillers dried grains with solubles (DDGS) is the coproduct of bioethanol production, derived from various cereal grains (corn, wheat, sorghum, rye, etc.) (Singh et al., 2002). Corn is the major material for ethanol production in the US. Corn contains 60-70% starch, 30-40% non-starch components such as protein, fiber, oil and ash. For DDGS production, a dry-grind process is the typical method due to low cost and simple equipment (Belyea et al., 2004). During the process, grains are ground and mixed with water to form a slurry. The slurry is cooked to liquefy the starch and saccharified with enzymes. Finally, yeasts are utilized to ferment sugars to produce ethanol. As ethanol is separated by distillation, the remaining unfermented residues (protein, oil, fiber and ash) are centrifuged, dried and mixed to produce the co-product known as DDGS (Bothast and Schlicher 2005, Liu 2009). The development in DDGS supply due to the growth in US fuel ethanol production has resulted in the need for continued market (Rosentrater, 2008).

Currently, DDGS is mainly used as feed for ruminants such as cattle and is applied at low level in poultry and swine diets because of high fiber content (Srinivasan et al., 2009). For improving the values of DDGS, separation of fiber, protein and fat may increase the utilization of DDGS. The fiber enriched fraction could be utilized for production of cellulosic ethanol, fiber oil, fiber gum, phytosterols, oligosaccharides and so on (Doner et al., 1998, Crittenden and Playne, 1996, Buhner and Agblevor, 1994); the dried fraction of non-fiber not only enhances the nutritional values but expands the market share (Buchana, 2002, Srinivasan et al., 2007, Liu 2009). Ruminants also need high fiber in their diet, so this new shift will increase the value of DDGS in the cattle industry.

Based on the physical properties of DDGS (Rosentrater, 2006; Ganesan et al., 2007), various fractionation processes have been investigated in looking for the efficient separation. Wu and Stringfellow (1986) used simple dry sieving fractionation of corn DDGS. Singh et al., (2002) investigated air aspiration to separate fiber from DDGS, limited success had been shown and the fiber fraction was mainly from pericarp fiber. Srinivasan et al., (2005) applied sieving and elutriation in fractionation process. First, DDGS was sieved into various particle size categories then elutriation was used to separate the fiber based fraction. Elutriation is defined as the separation of particles by an upward flowing stream of fluid; however, aspiration is defined as the act or result of removing or drawing by suction. Sieving and elutriation separate the fractions based on the combined effect of particle density, shape and size. Srinivasan and Singh (2008) researched fiber separation from DDGS using sieving and air classification. They found that density, shape, spherical properties had a direct effect on the terminal velocity of DDGS particles. This terminal velocity determines our ability to achieve an effective separation of the DDGS fractions.

In DDGS, fiber possesses a lower density than the non-fiber components. As air flows through DDGS, fiber as well as some small non-fiber components are carried away. Because fiber has long and needle-like shape, and it is easy to agglomerate with protein and oil to form particle with various particle sizes. Generally, a fiber-rich fraction has larger particle size and light density; by contrary, protein and oil rich fraction has small particle with high density profile due to their molecular structure property. For obtaining a valuable protein and oil rich DDGS fraction, different velocities of airflow are used to remove fiber selectively depending on their physical properties. At higher air velocity, air would carry all sizes of fiber, but the carryover of non-fiber components would be high (Srinivasan et al., 2005). Hence it is effective to sieve DDGS into different particle sizes first and aspiration is applied in each size category at proper velocities for gaining the better yields of DDGS fractionation with higher protein and oil contents. However, these researches mainly focused on particle size effect of DDGS and not indicated other factors which could influence the fractionation efficiency. The different air flow velocities and fractions collected from aspiration process could also give the effects on the final fractionation efficiency. Additionally, an estimating model which includes possible variables for fractionation could be a tool for a more comprehensive investigation of DDGS fractionation process.

In this study, sieving and aspiration were used to fractionate DDGS for obtaining high protein and oil contents, which could increase value of coproduct from corn-based ethanol industry. Also, different variables, air flow velocities, particle sizes and fraction factors, are considered in the fractionation including single variable effect and the effect derived from interactions of each variables. Otherwise, the terminal air flow velocity was determined by Iowa blower which was used as the references for different air flow velocity settings, and the relationships of protein and oil contents among different operating variables and the estimating models were also investigated by multivariate linear regression.

2. Materials and Methods

2.1 Materials

DDGS samples were collected from Lincoln Way Energy in Nevada IA, and stored at room temperature until further processing was done.

2.2 Methods

2.2.1 Sieving

For obtaining the particle size distribution, a sieving procedure was conducted based on the ASAE standard method (ASAE Standard, 2003). Air dried DDGS was sent through a machine sieve with 10, 20, 40, and 60 mesh. The mass of material remaining on each pan was collected and measured for individual weight. The distributions of four sieved fractions were calculated following Eq.1

$$Particle\ size\ distribution = \frac{W_{DDGS\ remained\ on\ each\ sieve}}{W_{total\ DDGS}} \times 100\% \qquad \text{Eq. 1}$$

2.2.2 Terminal Air Flow Velocity

For determining the terminal velocity of airflow applied in aspiration, we first used an Iowa Blower, which is developed by Seed Science Center, Iowa State University. The Iowa Blower (Fig. 9-1) is a small scale aspirator which separates sample into two fractions. There are five indexes of airflow forIowa blower,20, 40, 60, 80 and 100, which correspond to flow rates of 0.32, 1.54, 2.42, 2.85 and 3.06 MPS (m/sec) respectively. The distributions of two fractions are shown in Table 9-1. According the results, the terminal velocities for light and heavy weight fraction of 10-20 mesh and 20-40 mesh DDGS were between 0.32 and 1.54, and 3.06 MPS individually.

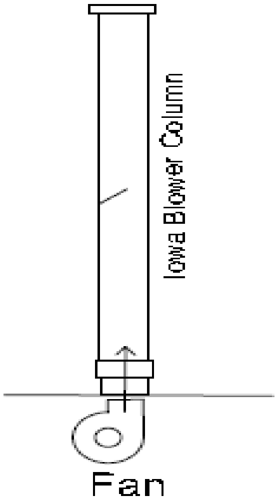

Fig. 9-1 Configuration of Iowa blower

Table 9-1 Mass distribution of DDGS through the Iowa blower

		10-20 mesh		20-40 mesh	
Airflow index	Flowrate (m/sec)	Light (%)	Heavy (%)	Light (%)	Heavy (%)
20	0.32	0	100	0	100
40	1.54	5	95	18.51	81.49
60	2.42	49	51	89.24	10.76
80	2.85	83.4	16.6	99.20	0.80
100	3.06	84	16	99.60	0.40

2.2.3 Aspiration

Aspiration was performed using a Carter Day lab-scale aspirator (Fig. 9-2). The equipment consisted of an electric fan, air-intake control, air separation chamber, rolling feeder and four fraction pans. During operation, the fan forced air into air separation chamber. DDGS was fed by rolling feeder with a constant rate of 100 g/min. The airflow delivered lighter DDGS to exit from the separation chamber, the heavier part of DDGS remained in the first fraction. The aspirator breaks the sample into 4 fractions based upon density, weight, and particle size.

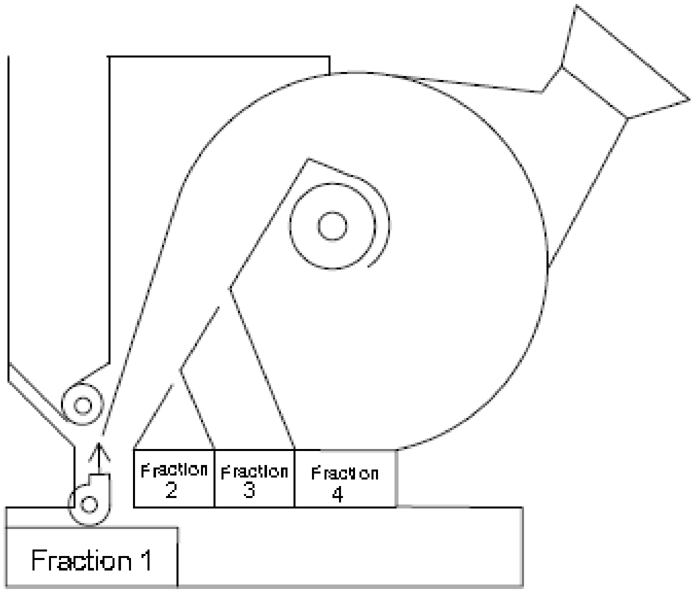

Fig. 9-2 Configuration of aspirator

According to the results of terminal airflow test by Iowa Blower and different profiles of DDGS, four levels 1.22, 1.83, 2.44, and 3.05 MPS of flow rates were applied for sieved fractions (original, 10-20mesh and 20-40 mesh). In this study, the particle sizes and air flow velocity are two main variables. The treatments are shown in Table 9-2. Each treatment was done by triplicate.

Table 9-2 Treatments used for DDGS aspiration

Treatment	Particle size	Air flow velocity (m/sec)
1	Original	1.22
2	Original	1.83
3	Original	2.44
4	Original	3.05
5	10-20 mesh	1.22
6	10-20 mesh	1.83
7	10-20 mesh	2.44
8	10-20 mesh	3.05
9	20-40 mesh	1.22
10	20-40 mesh	1.83
11	20-40 mesh	2.44
12	20-40 mesh	3.05

2.3 Analysis

2.3.1 Nutrient Content

The original and all fractions of DDGS through sieving and aspiration processes were analyzes for contents of moisture, fiber, protein, oil (fat) and ash. Ash content was determined based on AOAC official method 942.05 (Thiex and Novotny, 2012). Moisture, protein, fiber and oil contents were determined by NIR (Near Infrared Spectroscopy) (Dickey-John Instalab 800).

2.3.2 Efficiency of Nutrient Concentration

After combining sieving and aspiration processes, the nutrient contents were altered especially in protein, fiber and oil. These changes correspond to the different density profiles of each fraction. The efficiency of fractionation was calculated by Eq. 2. When the efficiency was positive, that indicates the nutrient (protein and oil) was condensed; otherwise, a negative value indicates the composition of nutrients had decreased. The calculation was performed based on the mean nutrient content of triplicate measurements.

$$Efficiency = \frac{W_{after\ treatment} - W_{original\ nutrient}}{W_{original\ nutrient}} \times 100\% \qquad \text{Eq. 2}$$

2.3.3 Statistical Analysis

Data are analyzed by JMP v.10 (JMP, Cary NC, USA). Mean and standard deviation are determined. Particle size, air flowrate and different DDGS fraction after aspiration are set as independent variable to perform the analysis of variance (ANOVA) and linear regression which were altered during the treatments. Tukey's HSD (honesty significant difference) was applied for conducting mean separation tests. Also, the response surface methodology (RSM) was conducted by TableCurve 3D (Systat Inc., CA, USA) to exam the trend and DDGS nutrient content changes caused by independent variables.

3. Results and Discussions

3.1 Mass and Nutrient Distribution

DDGS was divided into four fractions (above 10 mesh, 10-20 mesh, 20-40 mesh, and through 40mesh) by sieving primarily; the particle sizes with 0.85-2mm had the greatest occurrence about 61% followed by the particle sizes with 0.425-0.85mm of about 30% occurrence The average particle size of the original DDGS was about 0.75mm.

According to results of mass distribution, particle sizes with 0.85-2 mm, 0.425-0.85 mm and original DDGS (0.75mm) were chosen for the nutrients composition analysis by NIR (Table 9-3) and further aspiration separation test. According to the nutrient analysis, smaller particle sizes has higher protein content about 32%; additionally, DDGS with larger particle size has higher oil content about 10.8%. These results are relating to the particle densities of different nutrients (Barbosa-Canovas et al., 2005, Liu 2008). Fiber tends to agglomerate with other components to form a matrix. Thus, during the primary sieving, fiber doesn't show the obvious differences comparing to the original DDGS.

Table 9-3 Nutrient distribution and components of DDGS due to primary sieving

	Particle Size (mm)	Density (kg/m^3)	Moisture (%)	Ash (db %)	Nutrient Distribution (db %)		
					Protein	Oil	Fiber
10-20 mesh	0.85-2	96.99	9.30	4.83	29.23	10.82	6.54
Original	0.75	113.38	8.90	4.85	31.47	10.58	6.74
20-40 mesh	0.425-0.85	117.05	8.32	4.79	32.21	10.49	6.71

3.2 Aspiration Fractionation

Two different particle sizes of DDGS obtained from primary sieving, and the original DDGS were then fractionated by the aspirator. During aspiration, the DDGS was separated into 4 fractions, and the nutrient composition of these fractions shifted because the aspiration process separates the nutrients depending on their different densities. The various independent variables including flowrate, particle sizes and different fractions play a critical role for the final results. However, these factors have interactions which also affected the changes in protein, fiber and oil content of each DDGS fraction as well.

The effects on protein, fiber and oil content of DDGS which were treated by sieving and aspiration are shown in Table 9-4. Results include individual and multiple interactions. The means and standard deviations of protein, fiber and oil contents after the treatments are shown in Table 9-5. The number of fraction 1 to 4 represents the density of DDGS collected from these fractions from high to low. For protein and oil, they were concentrated in the first fraction, especially with the highest level of air flowrate (3.05 m/sec). That indicates these two nutrients have the higher mass density. However, in the aspect of different particle sizes, the smallest particle sizes with 0.425-0.85 mm have remarkably higher content of protein and oil in the first fraction with 40.81% and 17.64%, respectively. This result also indicates these two nutrients possess smaller particle size generally.

Table 9-4 Individual factor and interaction results for nutrients content of fractionated DDGS

		Protein		Fiber		Oil	
Sources	DF	F ratio	P value	F ratio	P value	F ratio	P value
Flowrate	3	123.34	<0.0001	29.893	<0.0001	353.69	<0.0001
Particle sizes	2	1096.88	<0.0001	20.512	<0.0001	218.35	<0.0001
Fraction #	3	1070.79	<0.0001	21.52	<0.0001	3971.65	<0.0001
Flowrate*Particle sizes	6	13.53	<0.0001	38.97	<0.0001	4.44	<0.0001
Flowrate*Fraction #	9	5.86	<0.0001	32.84	<0.0001	63.90	<0.0001
Particle sizes*Fraction #	6	44.83	<0.0001	103.36	<0.0001	11.88	<0.0001
Flowrate*Particle sizes *Fraction#	18	2.34	0.0043	15.36	<0.0001	4.44	<0.0001

Each treatment combination of statistical analysis is based on α=0.5

As for fiber, it is easy to agglomerate with other constituents because of structure and physical properties. The effects on fiber content are influenced by different combinations of factors.

Table 9-5 Sieving and aspiration treatment effects on nutrient composition of fractionated DDGS

		Protein (%)			Fiber (%)			Oil (%)		
Flowrate (m/sec)	Fraction #	0.85-2 mm	0.75 mm	0.425-0.85 mm	0.85-2 mm	0.75 mm	0.425-0.85 mm	0.85-2 mm	0.75 mm	0.425-0.85 mm
3.05	1	37.91	38.48	40.81	6.83	6.76	5.66	15.51	16.63	17.64
		(0.70)	(1.07)	(0.20)	(0.01)	(0.09)	(0.13)	(0.40)	(0.22)	(0.47)
	2	30.50	32.97	34.66	6.71	6.77	6.79	11.08	11.16	11.00
		(0.81)	(0.34)	(0.71)	(0.05)	(0.05)	(0.03)	(0.47)	(0.24)	(0.14)
	3	28.69	31.94	34.20	6.64	6.71	6.76	9.87	10.03	10.31
		(0.11)	(0.57)	(0.31	(0.05)	(0.05)	(0.01)	(0.27)	(0.18)	(0.31)
	4	25.57	32.02	32.30	6.53	6.78	6.82	8.89	9.38	9.77
		(0.38)	(0.34)	(0.25)	(0.04)	(0.05)	(0.02)	(0.06)	(0.06)	(0.13)
2.44	1	36.39	37.97	39.33	6.90	6.84	6.44	14.77	15.31	16.98
		(0.79)	(1.32)	(0.86)	(0.03)	(0.01)	(0.26)	(0.48)	(0.25)	(0.63)
	2	29.33	32.57	34.50	6.74	6.80	6.80	10.49	10.44	10.58
		(0.26)	(0.28)	(0.73)	(0.03)	(0.03)	(0.01)	(0.26)	(0.15)	(0.27)
	3	27.79	32.29	32.95	6.66	6.79	6.79	9.56	9.66	10.04
		(0.51)	(0.12)	(0.33)	(0.04)	(0.03)	(0.03)	(0.22)	(0.10)	(0.12)
	4	25.70	31.65	31.5	6.61	6.81	6.81	8.71	9.12	9.71
		(0.46)	(0.74)	(0.14)	(0.07)	(0.01)	(0.02)	(0.10)	(0.04)	(0.03)
	4	24.58	30.74	32.00	6.46	6.79	6.84	8.70	9.12	9.62
		(0.33)	(0.42)	(0.68)	(0.04)	(0.05)	(0.01)	(0.09)	(0.06)	(0.05)

Values in parentheses are standard deviations

Table 9-5 Continued

		Protein (%)			Fiber (%)			Oil (%)		
Flowrate (m/sec)	Fraction #	0.85-2 mm	0.75 mm	0.425-0.85 mm	0.85-2 mm	0.75 mm	0.425-0.85 mm	0.85-2 mm	0.75 mm	0.425-0.85 mm
1.83	1	35.18	37.60	39.34	6.89	6.84	6.59	13.82	14.42	15.88
		(0.53)	(0.41)	(1.75)	(0.04)	(0.04)	(0.09)	(0.36)	(0.40)	(0.34)
	2	28.95	32.57	34.16	6.70	6.82	6.90	9.73	9.94	10.38
		(0.31)	(0.80)	(0.50)	(0.03)	(0.05)	(0.01)	(0.27)	(0.19)	(0.17)
	3	26.47	31.88	32.69	6.60	6.78	6.81	9.04	9.48	9.67
		(0.30)	(0.39)	(0.26)	(0.04)	(0.03)	(0.06)	(0.11)	(0.14)	(0.11)
	4	24.58	30.74	32.00	6.46	6.79	6.84	8.70	9.12	9.62
		(0.33)	(0.42)	(0.68)	(0.04)	(0.05)	(0.01)	(0.09)	(0.06)	(0.05)
1.22	1	32.66	35.22	38.20	6.82	6.78	6.87	11.76	11.59	13.56
		(0.42)	(0.12)	(1.57)	(0.01)	(0.03)	(0.02)	(0.39)	(0.16)	(0.17)
	2	25.54	30.52	33.23	6.63	6.70	6.86	8.74	9.37	9.91
		(1.06)	(0.49)	(0.17)	(0.04)	(0.02)	(0.04)	(0.26)	(0.14)	(0.05)
	3	23.60	30.66	31.17	6.47	6.57	6.79	8.39	8.96	9.45
		(0.66)	(1.38)	(0.34)	(0.04)	(0.09)	(0.05)	(0.06)	(0.23)	(0.04)
	4	24.65	30.70	31.38	6.36	6.33	6.74	9.41	8.88	6.59
		(0.54)	(0.11)	(0.35)	(0.15)	(0.02)	(0.05)	(0.33)	(0.13)	(0.08)

Values in parentheses are standard deviations

As for fiber, it is easy to agglomerate with other constituents because of structure and physical properties. The effects on fiber content are influenced by different combinations of factors.

3.2.1 Protein Content

For DDGS, protein content is a critical issue for further utilization. According to the statistical analyses (Table 9-4), the individual factors, two factor interactions and all three factor interactions all have significant evidence that indicate these factors cause different effects on the protein content after sieving and aspiration treatment.

In single factors, higher flowrate and the fraction with higher density result in better ability to concentrate the protein content; also, the smaller particle size fraction is consisted of higher protein content. For binary variable combinations, when the DDGS with smaller particles was treated with higher flowrate, the protein content can be raised significantly. This result indicates protein has higher density than other components, which are easily carried away by air. In other words, the DDGS with higher protein content is able to withstand the high air flowrate and remained in the heavy fraction which is also attributed to high density property derived from protein.

According to response surface analysis (Fig. 9-3), as combining these three independent variables, as DDGS with 0.425-0.85mm was treated by flowrate of 3.05 m/sec; the optimal protein content collected in the first fraction could reach about 41%. By contrary, the DDGS with the largest particle size 0.85-2mm treated by flowrate of 1.22 m/sec has the lowest protein content about 23.6% from the fourth fraction. These results indicate that different combinations of variables can efficiently increase the protein content of DDGS fractions.

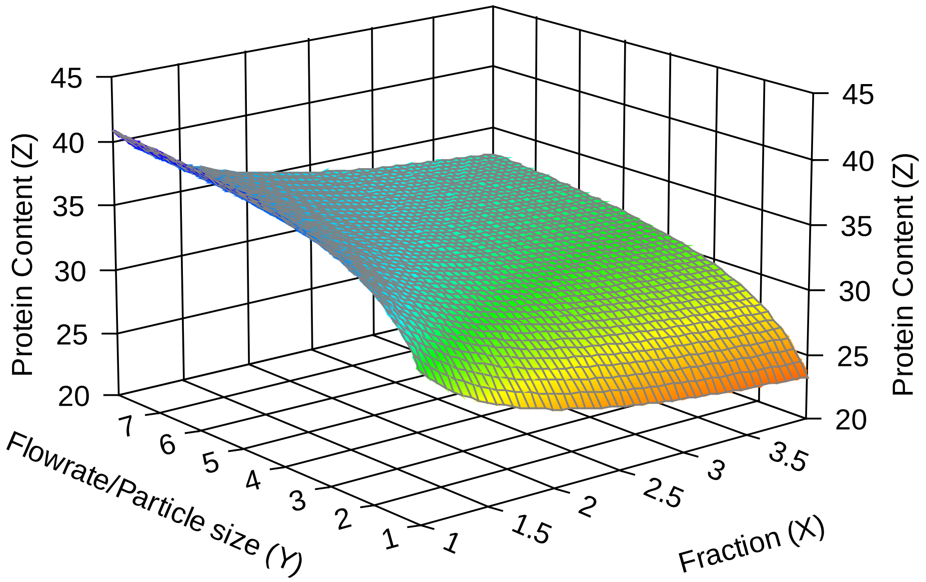

Fig. 9-3. Response surface of protein content and variables

Also, the relationship between protein content and all independent variables can be expressed as Eq. 3 with R^2 of 0.8. In the equation, Z dependent variable represents the prediction of protein content which can be estimated by x and y which are different fractions after aspiration process and the ratio of flowrate to particle size individually. Also, the protein content of DDGS after fractionation could be estimate based on this equation.

$$Z = 35.50 + \frac{10.69}{X} - \frac{15.27}{Y^{0.5}} \qquad \text{Eq. } 3$$

3.2.2 Oil Content

Oil (fat) is another critical nutrient of DDGS, and it can be utilized in animal feed as well. According to the results shown in Table 9-4, there is evidence to indicate that single, binary and triple factors all have effects and interactions on the final oil content after sieving and aspiration fractionation.

From the results, in the single variable, the trend is similar to protein content. Higher flowrate, smaller particle and the fraction with higher density has higher oil content which were 11.46%, 11.25% and 14.7%, respectively. Compared to the original DDGS, the oil content is increased about 1-4%. For the binary factor interactions, the combination of any two independent variables, higher flowrate, smaller particle size and higher density fraction, remarkably has the higher oil content especially flowrate of 3.05 m/sec for the first fraction where 16.57% oil content was achieved. This demonstrates that oil exists with smaller particles and larger density. Hence, oil rich DDGS can be obtained from the fraction with higher density.

As to interactions among these three variables shown in the result of response surface analysis (Fig. 9-4), the combination of 3.05 m/sec flowrate, smallest particles (0.425-0.85mm) and the fraction with the highest density increased the oil content to 17.63%. The result also indicates that there is the positive effect on concentrating oil content in DDGS by these three factors for sieving and aspiration gractionation. The relationship between oil content and variables can be expressed as Eq. 4 with R^2 of 0.97 as well, where Z-axis represents protein content; x- and y-axis indicate different fractions after fractionation processes and the ratio of flowrate to particle size respectively.

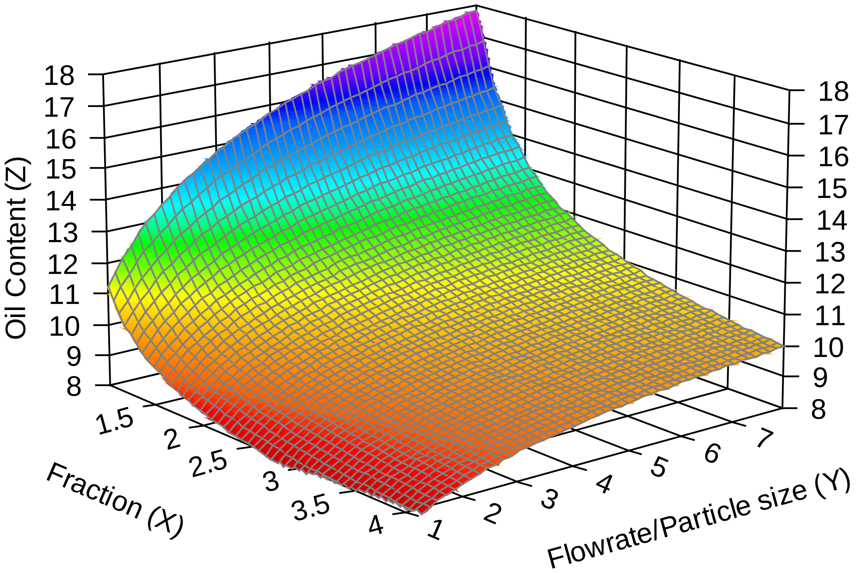

Fig. 9-4. Response surface of oil content and variables

$$\frac{1}{Z} = 0.09 - \frac{0.06}{X} + \frac{0.05}{Y^{0.5}} \qquad \text{Eq. 4}$$

3.2.3 Fiber Content

Fiber in DDGS is from the unfermented grain residues especially from corn hulls. Hence, the hull content is not as high as oil and protein. In the single factor effect, the mild flowrate, 1.83 and 2.44 m/sec, and the middle fraction lead to higher fiber contents, which were 6.75% and 6.77% individually. Generally, fiber has larger particles and lower density. From the results, it could be explained as agglomeration among fiber, protein and oil. Therefore, a mild condition used in fractionation is able to keep more fiber remained in DDGS which is opposite to obtain oil- and protein-rich DDGS requiring extreme condition for fractionation.

In binary independent variable effects, the higher fiber content does not show the expected result, which can be obtained from the fraction with lowest density. However, the highest was 6.8% in the lowest flowrate-highest density fraction, lowest flowrate-smallest particle sizes, and lowest density fraction-and smallest particle size group. This situation might reflect the interactions between fiber and other nutrients in the DDGS. Because fiber forms matrix-like particles with protein and oil, and it is possible to concentrate protein and oil during aspirating to cause this result.

As all variables were combined together as shown in Fig. 9-5, a mild flowrate had the highest fiber content about 6.9% no matter which fraction and particle size were used. And, the relationship between fiber content and variables can be expressed as Eq. 5 with R^2 of 0.8, where Z-axis represents protein content; x- and y-axis indicate different fractions after fractionation processes and the ratio of flowrate to particle size respectively.

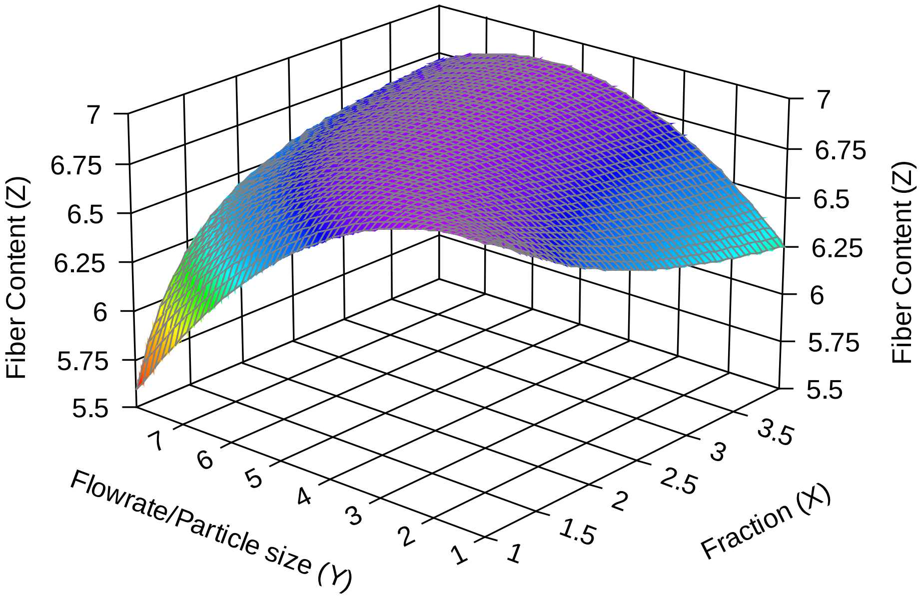

Fig. 9-5. Response surface of fiber content and variable

$$Z = 5.45 + \frac{2.23}{X} + 0.40Y - \frac{0.82}{X^2} - 0.03Y^2 - 0.34\frac{Y}{X} \qquad \textbf{Eq. 5}$$

From these results, it can be concluded briefly that fiber is easy to agglomerate with other constituents and thus becomes difficult to separate by physical treatment for concentrating fiber.

3.2.4 Other Components

The results of other components including moisture and ash contents are shown in Table 9-6. The moisture content varied during the aspiration process. Higher flowrate resulted in the lower moisture content. However, in different fractions after aspiration, the fourth fraction (lightest) had the lowest moisture content. An explanation could be the lighter DDGS was blown further, and the time DDGS contacted with air was longer than others. From these results, aspiration can be regarded as a partial drying process. Additionally, each single factor and the interactions between or among all independent variables had effects on the moisture content of DDGS during the fractionation process (Table 9-7).

Table 9-6 Sieving and aspiration treatments on other components of fractionated DDGS

		Moisture Content (%)			Ash (db %)		
Flowrate (m/sec)	Fraction #	0.85-2 mm	0.75 mm	0.425-0.85 mm	0.85-2 mm	0.75 mm	0.425-0.85 mm
3.05	1	7.29	7.62	7.59	4.47	4.70	4.63
		(0.04)	(0.44)	(0.40)	(0.21)	(0.21)	(0.21)
	2	9.24	8.64	8.01	4.43	4.67	4.33
		(0.37)	(0.48)	(0.57)	(0.15)	(0.23)	(0.06)
	3	9.81	8.32	7.71	4.67	4.63	4.57
		(0.06)	(0.23)	(0.06)	(0.32)	(0.15)	(0.06)
	4	10.78	8.62	8.72	4.57	4.63	4.57
		(0.16)	(0.10)	(0.06)	(0.21)	(0.06)	(0.21)
2.44	1	8.05	7.29	7.56	4.37	4.93	4.33
		(0.17)	(0.26)	(0.32)	(0.31)	(0.29)	(0.25)
	2	9.86	8.57	7.94	4.40	5.03	4.37
		(0.13)	(0.09)	(0.29)	(0.35)	(0.21)	(0.15)
	3	10.30	8.58	8.27	4.60	4.87	4.37
		(0.17)	(0.22)	(0.12)	(0.10)	(0.21)	(0.21)
	4	10.99	8.73	9.14	4.60	4.90	4.73
		(0.20)	(0.60)	(0.06)	(0.10)	(0.46	(0.31)

Values in parentheses are standard deviations.

Table 9-6 Continued

		Moisture Content (%)			Ash (db %)		
Flowrate (m/sec)	Fraction #	0.85-2 mm	0.75 mm	0.425-0.85 mm	0.85-2 mm	0.75 mm	0.425-0.85 mm
1.83	1	8.25	7.57	7.56	4.33	4.93	4.67
		(0.19)	(0.15)	(0.21)	(0.25)	(0.15)	(0.32)
	2	9.92	8.73	8.49	4.50	4.80	4.30
		(0.20)	(0.54)	(0.20)	(0.20)	(0.36)	(0.26)
	3	10.59	8.72	8.60	4.53	5.03	4.37
		(0.10)	(0.05)	(0.24)	(0.25)	(0.38)	(0.12)
	4	11.07	9.23	9.04	4.47	5.10	4.63
		(0.22)	(0.12)	(0.29)	(0.21)	(0.30)	(0.25)
1.22	1	9.03	7.66	6.87	4.37	4.93	4.67
		(0.07)	(0.06)	(0.42)	(0.29)	(0.32)	(0.06)
	2	11.12	8.88	8.64	4.80	5.03	4.57
		(0.25)	(0.19)	(0.17)	(0.70)	(0.31)	(0.15)
	3	11.36	7.96	9.04	4.47	4.87	4.53
		(0.33)	(0.33)	(0.20)	(0.12)	(0.21	(0.06)
	4	11.16	7.02	8.83	4.50	4.73	4.67
		(0.83)	(0.60)	(0.28)	(0.20)	(0.23)	(0.06)

Values in parentheses are standard deviations.

Table 9-7 Individual factor and interaction results for other components of fractionated DDGS

Sources	DF	Moisture		Ash	
		F ratio	P value	F ratio	P value
Flowrate	3	12.21	<0.0001	1.69	0.17
Particle sizes	2	236.84	<0.0001	32.57	<0.0001
Fraction #	3	128.15	<0.0001	0.24	0.87
Flowrate*Particle sizes	6	5.43	<0.0001	1.64	0.15
Flowrate*Fraction #	9	2.49	0.0132	1.15	0.33
Particle sizes*Fraction #	6	11.31	<0.0001	1.32	0.25
Flowrate*Particle sizes *Fraction#	18	1.8	0.036	0.63	0.87

Each treatment combination of statistical analysis is based on α=0

The ash content varied among DDGS samples from 4% to 5%. From Table 9-6 and Table 9-7, there were mixed trends of ash content depending on each factors except particle size. Generally, the original DDGS without primary sieving had slightly higher ash content. For the largest and the finest particle sizes, ash content decreased with sieving. From this point, the primary sieving process could concentrate the ash in the fraction with larger particle sizes. As for ash content, only particle size had a significant effect on DDGS with smaller the particle size had more ash content. This might be relative to the higher oil and protein contents in fractions with smaller particle size.

3.3 Efficiency of Sieving and Aspiration Fractionation

3.3.1 Protein

In addition to 3D response surface analysis used to estimate nutrients content after DDGS fractionation, a linear regression is used to express the relationship between the efficiency of fractionation and independent variables as well. The result of concentrating protein from DDGS is shown in Fig. 9-6. A positive efficiency indicates the fractionation process can concentrate and increase protein content, and vice versa.

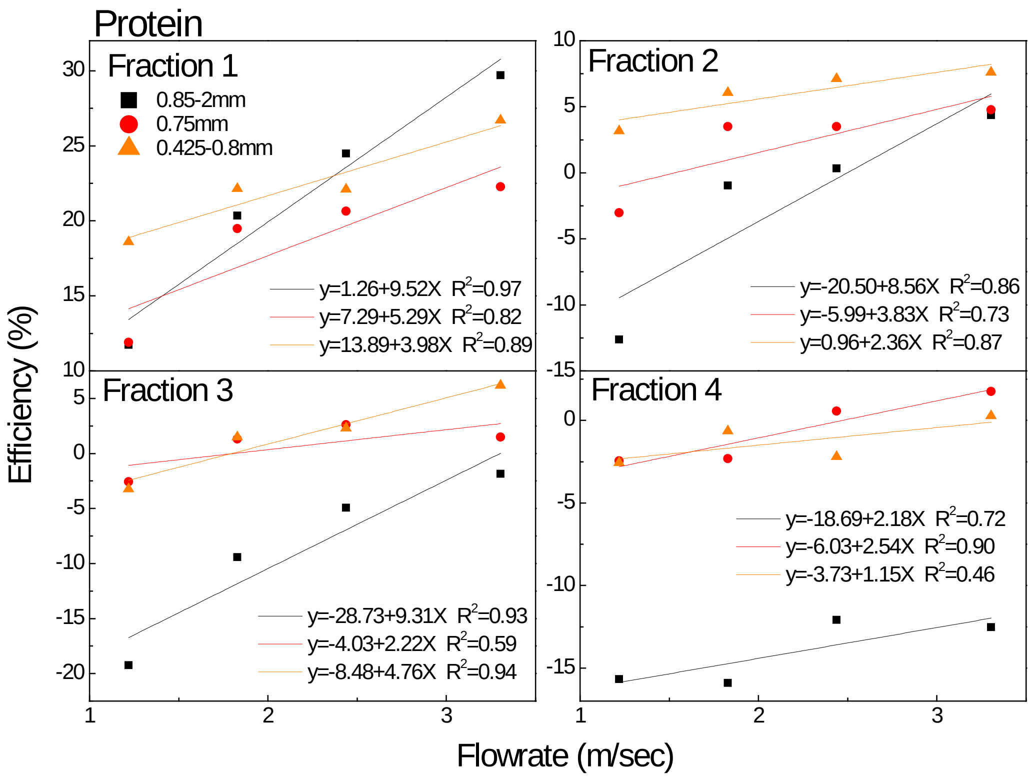

Fig. 9-6. Efficiency of sieving and aspiration for concentrating protein. Fraction 1: Heavy fraction; Fraction 2: Mid-heavy fraction; Fraction 3: Mid-light fraction; Fraction 4: light fraction.

The highest efficiency was about 30% from the first fraction treated with 3.05 m/sec flowrate. As the flowrate and the density of fraction decreased, the efficiency got lower. According to the results, a simple linear relationship between flowrate and the efficiency can be observed for each fraction. Comparing these four fractions, the higher efficiency has the better linear trend with higher R squares; however, in fraction 4, a linear relationship is not well performed might be resulted from lower protein content and concentrating efficiency in the fourth fraction.

Due to linear relationships existing between fractionation efficiency and 4 fractions and all particle sizes, the fraction is considered to be a variable for a linear regression considering all variables to have a new expression shown in Eq. 6, and it has a R^2 of 0.98. All variables have effects on the estimated efficiency which is corresponding to the previous results of variances analysis. Additionally, the explanatory Xs for particle size and fraction are regarded as dummy variables, which are substituted by 0 or 1 depending on the conditions of analysis. As predicting the efficiency of DDGS with 0.85-2mm from fraction 4, the Xs for particle and fractions are substituted by 0, and the estimated efficiency at any flowrate can be obtained. Therefore, the DDGS with 0.85-2mm from fraction 4 is the foundation of this combined expression. Through this equation, it is accessible to predict the efficiency of protein condensation by sieving and aspiration processes.

$$\begin{aligned}
y_{protein} \\
&= -24.09 + 4.7X_{flowrate} + 12.76X_{particle\ 0.425\sim 0.85} + 13.43X_{particle\ 0.75} + 35.62X_{fraction1} \\
&+ 11.82X_{fraction2} + 5.18X_{fraction3} - 4.33\left(X_{flowrate} - 2.135\right)X_{particle\ 0.425\sim 0.85} \\
&- 3.92\left(X_{flowrate} - 2.135\right)X_{particle0.75} + 4.3\left(X_{flowrate} - 2.135\right)X_{fraction1} \\
&+ 2.964.3\left(X_{flowrate} - 2.135\right)X_{fraction2} + 3.474.3\left(X_{flowrate} - 2.135\right)X_{fraction3} \\
&- 11.94\, X_{particle\ 0.425\sim 0.85}X_{fraction1} - 4.55\, X_{particle\ 0.425\sim 0.85}X_{fraction2} \\
&- 2.21\, X_{particle\ 0.425\sim 0.85}X_{fraction3} - 16.43\, X_{particle0.75}X_{fraction1} \\
&- 9.03X_{particle0.75}X_{fraction2} \\
&- 3.86X_{particle0.75}X_{fraction3} \qquad \text{Eq. 6}
\end{aligned}$$

$X_{flowrate}$: *Any flowrate*
$X_{particle\ 0.425\text{-}0.85}$: *1 for 0.425-0.85 mm particle size; 0 for others.*
$X_{particle\ 0.75}$: *1 for 0.75 mm particle size; 0 for others.*
$X_{fraction\ 1}$: *1 for fraction 1; 0 for others.*
$X_{fraction\ 2}$: *1 for fraction 2; 0 for others.*
$X_{fraction\ 3}$: *1 for fraction 3; 0 for others.*

3.3.2 Oil

The efficiency of oil separation (Fig. 9-7) had similar trends to protein because of their similar density profile trends. The best efficiency, about 70%, were obtained from the first fraction and the finer particle DDGS treated with 3.05 m/sec flowrate. The finer particles also has higher efficiencies to increase oil content. The result indicates DDGS with finer particle size tends to have higher oil content. From the results of protein and oil fractionation efficiency, particle size plays an important role for increasing oil and protein content in DDGS. Therefore, a primary sieving process is essential to increase the efficiency for concentrating oil and distinguishing the nutrients contribution of different fractions of DDGS.

From Fig. 9-7, linear trends between efficiency and flowrate are more obvious to be observed. A higher flowrate and is preferred to have higher efficiency. However, a negative slope and the lowest fitting performance of linear relationship is observed in the largest particle sized collected from the fourth fraction. This result also reflect trend discussed previously, oil tends to existing in small particle, and fiber is agglomerated with other nutrient to form as large particle with light density which would be easily carried away by air with high flowrate.

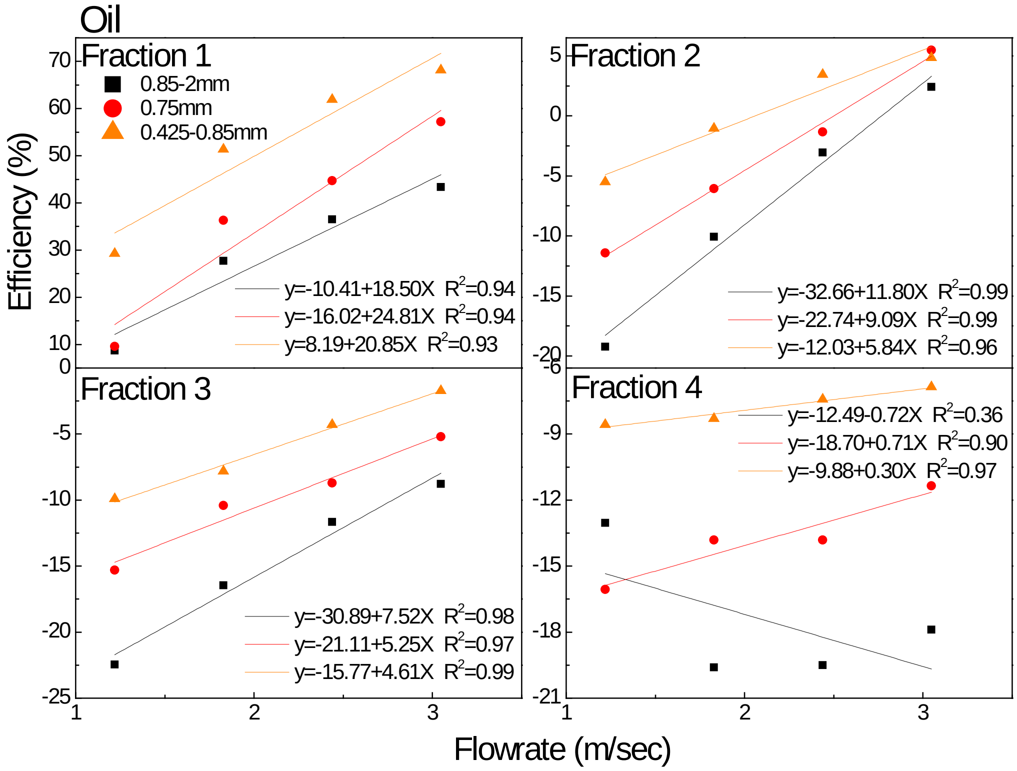

Fig. 9-7. Efficiency of sieving and aspiration for concentrating oil. Fraction 1: Heavy fraction; Fraction 2: Mid-heavy fraction; Fraction 3: Mid-light fraction; Fraction 4: Light fraction.

A linear combination of all variables including fractions was conducted and the R^2 of the expression is 0.97 (Eq. 7). These three variables all have significant effect on the efficiency which is similar to the previous variances analysis. Dummy variables, 0 and 1, are applied to substitute explanatory Xs of particle sizes and fractions as protein separation as well. The basic condition of oil separation at any flowrate is the DDGS collected from fraction 4 with 0.85mm particle size as the explained Xs are all substituted by 0. Otherwise, the expression also indicates that the highest efficiency at the certain flowrate were obtained from the finest particle size and the fraction with the highest density.

$$y_{oil} = -19.59 + 0.32X_{flowrate} + 12.53X_{particle\ 0.425\sim0.85} + 5.17X_{particle\ 0.75} + 7.61X_{fraction1} - 8.79X_{fraction2} - 8.9X_{fraction3} + 21.06X_{flowrate}X_{fraction1} + 8.59X_{flowrate}X_{fraction2} + 5.47X_{flowrate}X_{fraction3} \quad \text{Eq. 7}$$

$X_{flowrate}$: *Any flowrate*
$X_{particle\ 0.425\text{-}0.85}$: *1 for 0.425-0.85 mm particle size; 0 for others.*
$X_{particle\ 0.75}$: *1 for 0.75 mm particle size; 0 for others.*
$X_{fraction\ 1}$: *1 for fraction 1; 0 for others.*
$X_{fraction\ 2}$: *1 for fraction 2; 0 for others.*
$X_{fraction\ 3}$: *1 for fraction 3; 0 for others.*

3.3.3 Fiber

For fiber separation efficiency (Fig. 9-8), the trend is not uniform for each flowrate condition. The lowest efficiency was obtained from the first fraction of 0.425-0.85mm DDGS treated with 3.05 m/sec. That indicates the fiber is easy to blown away because of light mass weight. However, the trend of efficiency does not show the fraction with the lowest density that can achieve higher efficiency as expected.

From the Fig. 8, the linear relationships between efficiency and flowrate were fairly poor for every fraction. This indicates that flowrate had a limited effect on the efficiency of fiber separation. Because of the lack of linearity, it was hard to have a reliable linear combination expression for estimating the efficiency of fiber separation at any reasonable condition. As the result of previous experimentation, fiber is easy to agglomerate with other constituents. Hence, that might be the reason which results in this situation. This also demonstrates that the physical fractionation treatment is not a suitable approach for separating fiber. When protein and oil were concentrated during the aspiration, the fiber which formed matrixes with protein and oil at the same time. That will be the problem as using the physical separation treatment.

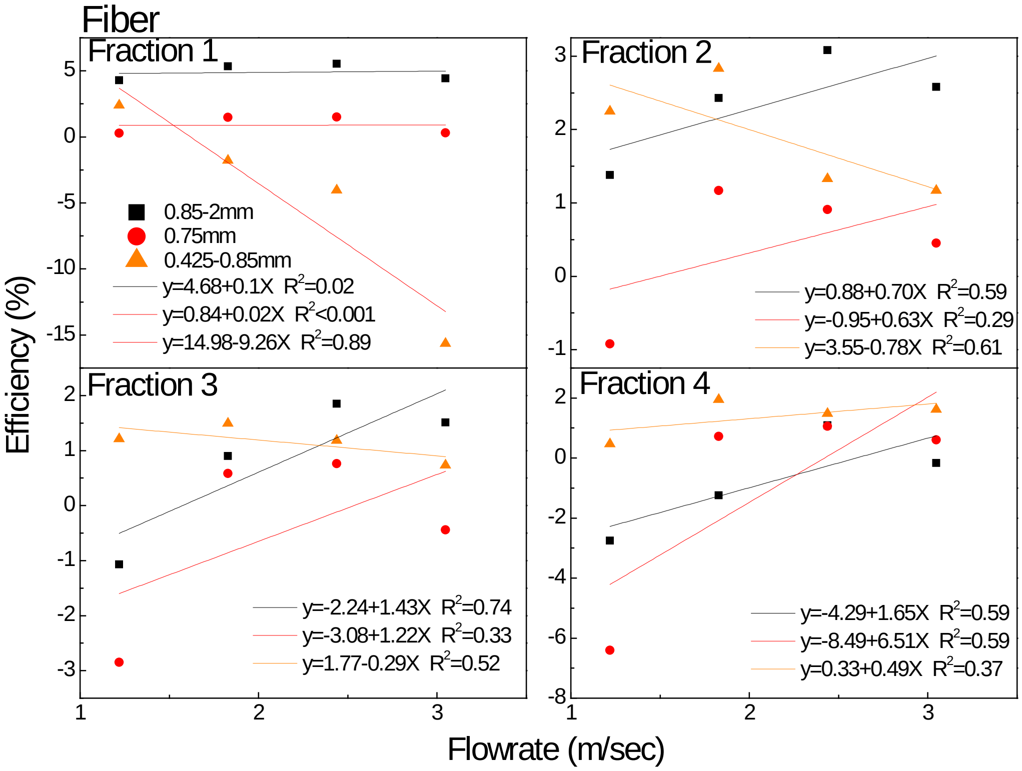

Fig. 9-8. Efficiency of sieving and aspiration for concentrating fiber. Fraction 1: Heavy fraction; Fraction 2: Mid-heavy fraction; Fraction 3: Mid-light fraction; Fraction 4: Light fraction.

4. Conclusions

In sieving and aspiration fractionation process, air flowrate, particle sizes and densities play a critical role in the final efficiency of nutrient separation. The effects of these variables highly correspond to the properties of these nutrients. For protein and oil, fractions with higher density, higher air flowrate and smaller particle sizes improve the efficiency of separation. However, there is a limitation for concentrating fiber content by physical fractionation treatment because fiber is easy to agglomerate with other nutrients. Additionally, the linear combination is able to estimate the efficiency of protein and oil separation at reasonable operation conditions.

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CHAPTER 10

CONCLUSIONS AND FUTURE WORK

1. Conclusions

Soybean extraction is the process which is used in the food and related industries. It can be regarded as a pretreatment for other applications. According to the TEA and EIA of these three extraction techniques, the results can be concluded in economic feasibility and environmental aspects as the following.

In the economic feasibility aspect:

(a) Extruding-expelling process is profitable when the capacity of soybean oil annual production is scaled up over 12.81million kg.

(b) Hexane extraction is a profitable process when the scale is larger than 173.22 million kg of annual soybean oil production.

(c) EAEP is profitable when the scale is larger than 17 million kg of annual soybean oil production.

(d) Soybean meal is the driving force for the extruding-expelling process due to its high productivity, nutrient values and selling price.

(e) Soybean meal is also the driving force for hexane extraction process due to its high productivity.

(f) The value of co-product has the major effect on EAEP profitability. Skim and insoluble fiber contribute over 70% of total revenue when they are sold as the source for soy-corn integrated ethanol production.

(g) Co-products, skim and insoluble fiber, are the driving force for EAEP. This result also indicates that EAEP is potential to have economic feasibility when connected to corn-based ethanol production as an integrated biorefinery system.

(h) Operating cost, especially the material cost, has the highest effect on profitability of the oil extraction processes.

In the environmental impact aspect:

(a) Hexane extraction has the highest environmental impact because the organic solvent is applied for the extraction.

(b) EAEP and extruding-expelling process have the similar environmental impact scores, and they are lower than the hexane extraction because there is no organic solvent applying in the process.

(c) Hexane has the lowest GHG and air pollutant emissions due to its high energy efficiency.

(d) Extruding-Expelling process has the higher GHG and air pollutant emissions because higher energy consumption is required during the extruding and pressing processes.

(e) EAEP also has the higher GHG emission than the hexane extraction because more energy consumptions are needed in the pretreatment process, especially for crop particle size reduction, and flake extruding.

(f) The main challenge for applying EAEP in the industry is how to make pretreatment processes more efficient.

In addition to the analyses of soybean oil extractions, the DDGS is another important co-product from the soy-corn integrated biorefinery system. Based on the sieving and aspiration technique, the efficiency of nutrient fractionation can be concluded as:

(a) Higher air flowrate used for finer DDGS particle can concentrate the oil and protein contents.

(b) Lower air flowrate used for larger DDGS particle can increase the fiber content.

(c) A proper combination of DDGS particle size and air flow rate is recommended to have DDGS with higher nutrient values and selling price.

2. Future Work

According to the results of this study, the EAEP has the potential to be applied in the industry which is profitable in the large scale operation and has lower environmental impacts than the conventional hexane extraction. In future work, the EAEP will be connected to corn-based ethanol refinery in the real operation. Also, the overall TEA and EIA of the soy-corn integrated biorefinery with soybean EAEP are investigated. The sensitivity analysis of GHG and air pollutant emissions will be investigated according to the changes of primary energy used for electricity generation.

Additionally, the social impacts including health and safety, quality of working condition, impact of employment, education training, innovative potential, societal product benefit etc., will be included as well. As the TEA, EIA, and the social aspects are used for soy-corn integrated biorefinery system with EAEP, then a well-rounded sustainability analysis of this developing system can be performed.

APPENDIX

ENERGY CONSUMPTION INPUTS

Table A-1 Energy Consumption of Extruding-Expelling Process

	Unit	Energy Consumption	Citation
Conveyor	kW/(m^3/h)m	0.08	Haas et al., 2006
Storage bin	kW/m^3	0.03	Haas et al., 2006
Drum dryer	kW/m^2	0.99	Haas et al., 2006
Grinder	kW/(kg/h)	0.01	Haas et al., 2006
Extruder	kW/(kg/h)	0.31	CCUR ISU
Expeller	kW/(kg/h)	0.31	Haas et al., 2006
Degumming tank	kW/m^3	2.00	CCUR ISU
Centrifuge	kW/(kg/h)	0.02	CCUR ISU
Dryer for oil recovery	kW/m^2	0.06	Haas et al., 2006
Meal grinder	kW/(kg/h)	0.01	Haas et al., 2006
Meal processer	kW/(kg/h)	0.01	Haas et al., 2006

Table A-2 Energy Consumption of Hexane Extraction Process

	Unit	Energy Consumption	Citation
Conveyor	kW/(m^3/h)m	0.08	Haas et al., 2006
Storage bin	kW/m^3	0.03	Haas et al., 2006
Drum dryer	kW/m^2	2.3	Haas et al., 2006
Grinder	kW/(kg/h)	0.01	Haas et al., 2006
Aspirator	kW/(kg/h)	0.05	CCUR ISU
Conditioner	kW/m^2	2.3	Haas et al., 2006
Flaking miller	kW/(kg/h)	0.01	Haas et al., 2006
Extractor	kW/(kg/h)	0.04	Haas et al., 2006
Toaster	kW/m^2	2.00	Haas et al., 2006
Degumming tank	kW/m^3	2.00	CCUR ISU
Centrifuge	kW/(kg/h)	0.01	CCUR ISU
Dryer for oil recovery	kW/m^2	0.06	Haas et al., 2006
Hexane receiving tank	kW/m^3	2.00	Haas et al., 2006
Hexane storage tank	kW/m^3	2.00	Haas et al., 2006
Meal grinder	kW/(kg/h)	0.01	Haas et al., 2006
Hull grinder	kW/(kg/h)	0.01	Haas et al., 2006
Meal processer	kW/(kg/h)	0.01	Haas et al., 2006

Table A-3 Energy Consumption of Enzyme Assisted Aqueous Extraction Process (Collected from CCUR, ISU)

	Unit	Energy Consumption
Screw conveyor	kW/(m^3/h)m	3.60
Silo/Bin	kW/m^3	0.03
Grinder	kW/(kg/h)	0.05
Flake miller	kW/(kg/h)	0.11
Aspirator	kW/(kg/h)	0.05
Extruder	kW/(kg/h)	0.31
Blending tank I	kW/m^3	2.03
Blending tank II		
Blending tank III		
3-phase decanter I	kW/(kg/h)	0.02
3-phase decanter II		
Disc-stack centrifuge I	kW	6.5
Disc-stack centrifuge II		
Storage tank	kW/m^3	2.00