



Economics of plant oil recovery: A review

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ARTICLE INFO

Keywords:

Plant oil production
On-farm pressing
Industrial mechanical pressing
Solvent extraction
Production cost

ABSTRACT

Plant oil is a major agricultural commodity used in food, feed, and chemicals. Presently plant oil is produced from oil seeds either using mechanical pressing or solvent extraction. These technologies have steadily improved for increased oil recovery; however, production cost is especially important for a commodity. Herein three technologies and their costs are reviewed for on-farm pressing, industrial mechanical pressing, and solvent extraction. Solvent extraction is the dominant technology because it offers high oil recovery and low production cost. In contrast, industrial mechanical pressing has the highest production cost because of its low oil yield; nevertheless, the simple process results in the lowest fixed capital investment. For on-farm pressing, lower material cost results in lower production cost than industrial mechanical pressing. Additionally, credits from co-products play an important role in determining total revenues, especially for mechanical pressing. Therefore, broadening the applications and values of the co-product is also critical for profitability for the plant oil industry.

1. Introduction

Plant oil is one of the most extensively used renewable feedstock in food, feed, biofuels, and chemicals production. Triglycerides are the major constituents of plant oil and have broad utility due to their ready availability, easy processing, chemical functionality, and relatively low cost (Zhang et al., 2017; Kumar et al., 2017). Major oilseeds on the global market include soybean, rapeseed, sunflower seed, peanut, cottonseed, palm kernel, and copra (USDA, 2018).

From 2013 to 2017, global oilseed production had increased about 15%. The US has been the largest oilseed producer in the world, producing 131.31 million metric tons of oilseeds in 2017 followed by Brazil, Argentina, and China. Soybean accounts for 91% of oilseed production in the U.S. (USDA, 2018). For worldwide plant oil production, palm oil (extracted from palm fruit) dominates followed by in decreasing order: soybean, rapeseed, sunflower seed, peanut, cottonseed, coconut, and olive oil. Indonesia and Malaysia are the largest producers of palm oil. Major soybean oil producers are China and the U.S. European Union countries produce primarily rapeseed oil; additionally, sunflower seed oil and olive oil are produced in eastern and southern Europe. China and India are two major producers of peanut and cottonseed oils (USDA, 2017). In the US, besides soybean, corn, canola, sunflower seed, cottonseed, and peanuts are other common oil crops (USDA, 2017).

In addition to its well-known food uses, plant oil is a platform chemical. The applications of oleochemicals include fuels, lubricants, surfactants, food additives, detergents, cosmetics, pharmaceuticals, and other chemical syntheses (Saxena et al., 1998; Kumar et al., 2017). Recently, some major chemical manufacturers have shifted to using plant oils as sustainable feedstock for producing polymers; therefore, the global oleochemical market is predicted to reach about USD 26.8 billion in 2022 (Grand View Research, 2016; Zion Market Research, 2017). The U.S. plant oil market is expected to reach USD 3.78 billion in 2024 (Grand View Research, 2016). With the growth of plant oil market, U.S. processors are expected to increase plant capacity up to about 5% from existing capacity, especially for soybean oil plant in 2019 (Hirtzer, 2017).

The oleochemical industry makes use of both fatty acids and glycerol. Fatty acids are produced by oil hydrolysis and glycerol is a side-product of both oil hydrolysis and biodiesel (Moser, 2009). These two products from plant oil are used for productions of epichlorohydrin (Bell et al., 2008; Caullet and Le Nôtre, 2015), acrolein (Pagliaro et al., 2007; Cortright et al., 2002; Zou et al., 2016; Garlapati et al., 2016), fatty alcohol (Voeste and Buchold, 1984), fatty acid esters (Freedman et al., 1984), fatty amines (Visek, 2003), and other polymers (Erhan and Bagby, 1994; Ronda et al., 2011) which are shown in Fig. 1.

There are numerous challenges facing the oleochemical industry to maintain financial sustainability. In addition to new technologies

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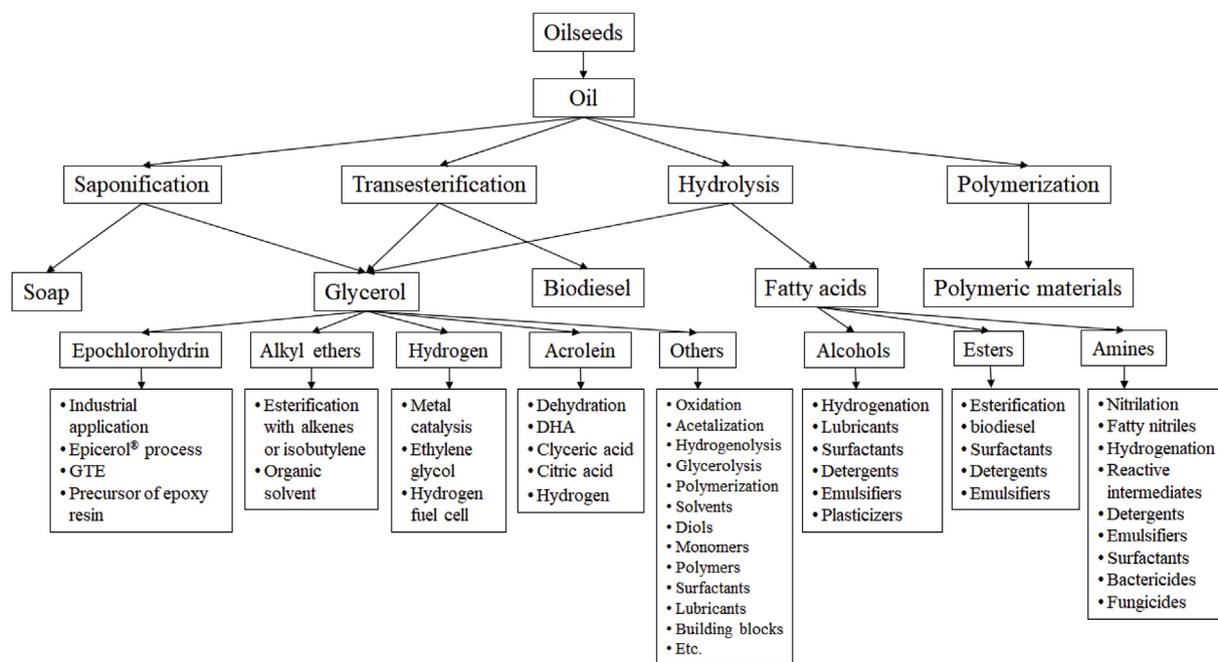


Fig. 1. Plant oleochemical applications.

developed for attaining high oil recovery, the economic viability is an essential consideration for a profitable venture. The material cost account for over 85% of total production costs which has been regarded as the main hurdle for a profitable investment (Haas et al., 2006). In the oleochemical industry, oil extraction and recovery have to be cost-effective and is highly related to an abundant crop supply and efficient processing technology.

Techno-economic evaluation of plant oil production or oleochemical production from different feedstocks has been previously reported (Haas et al., 2006; Vlysidis et al., 2011; Nevase et al., 2012; Wang, 2016; Huang et al., 2016; Ngo et al., 2014). However, there are still gaps in the detailed cost profile of plant oil production, especially for the industrial applications. Cheng and Rosentrater (2017) focused on the costs of soybean oil production by hexane extraction and comparing to the costs of soybean oil production by the mechanical pressing process (Cheng, 2017a) in industrial operations. Though different processing and oil extraction technologies used in the oil production are a critical factor in determining the production costs and the total investment, yield of oil-bearing crops and their oil concentration can significantly affect these costs.

In this review, oil production from solvent extraction and mechanical pressing, including on-farm oil production, industrial and commercial operations are investigated. The objective of this review is to provide an overview of plant oil production cost to form the basis for evaluating oil applications in the oleochemical industry.

2. Boundary definition, data collection, and cost estimation

2.1. Boundary definition

This study focuses on crude oil production and in particular does not include refining because product specification is application specific. For example, oil purchased at the grocery market is refined, bleached, and deodorized. Other applications require fatty acids or even a single fatty species. The steps included are oilseeds handling, oil extraction, and oil recovery (Fig. 2).

2.2. Literature review and data collection

Mechanical pressing and solvent extraction are the two dominant technologies used for extracting plant oil. Mechanical pressing is usually used for on-farm production and other small-scale operations located near harvest sites to reduce costs related to feedstock transportation (Darby and Callahan, 2015). However, on an industrial scale, much more oil is extracted by solvent extraction than by mechanical pressing (Cheng, 2017^a). Process costs for on-farm and small-scale oil press system are readily available in published literature. Large oil processing facilities primarily use solvents for oil extraction. Unexpectedly, there is a scarcity of published cost analysis data on solvent oil extraction process (Cheng and Rosentrater, 2017). Therefore, data from techno-economic models for the production of biodiesel and oleochemicals were used to extract oil production costs. Soybean, canola, sunflower, rapeseeds and other oil plants such as lipidcane and jatropha were covered in this study. Oil extracted from lipidcane and jatropha is not commercially available and the costs of lipidcane and jatropha oil were estimated based on the published studies.

2.3. Cost estimation

The minimum selling price for a commodity is determined by fixed and operating costs. A simple estimation of total fixed cost is based upon total (major) equipment cost using a “Lang Factor” multiplier. The Lang factor (Lang, 1947), which allows for installation cost, varies from 3 to 6 depending upon the processes and for plant oil extraction is 3.1–3.63 (Wolf, 2011). Operating costs includes capital required for purchasing raw materials, utilities, labor, and facility-related expenses.

Production costs, as is true of any commodity chemical produced by a mature industry, is dictated largely by the cost of the oilseeds net co-products. As oilseeds are sold on the open market, it follows that processors able to recover more gallons of oil per tonne of seed will command the lowest price. This put a premium on operating with very high oil recovery efficiencies (e.g. maximum kg of oil per kg of processed seed). The oil recovery efficiency of the mechanical pressing process is reported to be approximately at 70% (Huang et al., 2016; Cheng, 2017a); a 98% oil recovery efficiency is reported for the solvent extraction process (Marouli and Maroulis, 2005; Cheng and

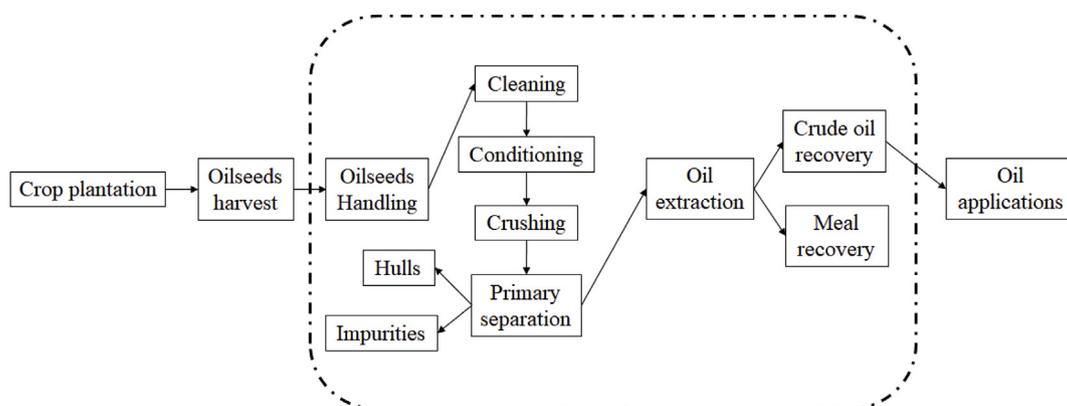


Fig. 2. The boundary definition of oil production cost analysis (circled by the dashed line).

Rosentrater, 2017). In this study, the US cases are mainly investigated, and the price was adjusted to 2017 value based on the inflation factor (US BLS, 2017).

3. Mechanical oil pressing

3.1. Mechanical pressing process

Use of mechanical pressing for plant oil, especially soybean oil, dates back to the early 1940s. The oil is extracted by feeding the seeds into either a hydraulic or continuous/expeller screw press (Markley and Gross, 1944; Ward, 1976; Nelson et al., 1987). Low oil recovery (e.g. 70%) is the prime disadvantage of the mechanical pressing process. Only 5% of plant oil plants use this technology (US EPA, 2001).

The mechanical pressing process is shown in Fig. 3. After being cleaned, the seeds are pre-conditioned for moisture and heated to break the oleosome structure before being crushed and pressed. To achieve higher oil recovery, high temperature is applied which often darkens the appearance of the oil and can even lead to its deterioration. The extruding-expelling process was introduced to mitigate the effects caused by operating at high temperature (Nelson et al., 1987). The extrudate of ground oilseeds with 10–14% moisture content acts as a semi-fluid, and the short residence time in the extruder generates sufficient heat (over 130 °C) to break down the oleosome structure. Extruding-expelling process results in higher oil recovery of over 70% (Nelson et al., 1987).

Heat and pressure are two critical factors for the mechanical pressing process. Mechanical pressing is an energy-intense process that requires higher utility costs (Cheng et al., 2018). Though there is no chemical addition in this process, the high energy consumption and the low oil recovery make it a less preferred process compared to solvent extraction for industrial applications.

3.2. On-farm and small-scale process

On-farm and small-scale oil pressing operations are used in the Midwest and Northeastern US (McIntosh et al., 1984; Fore et al., 2011;

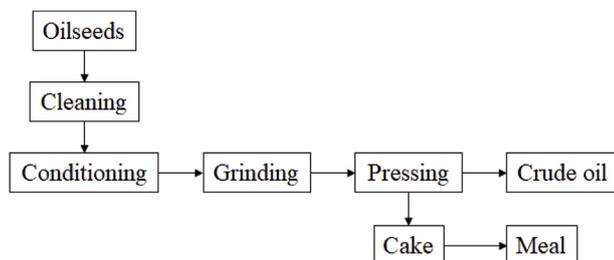


Fig. 3. The process of mechanical oil pressing.

White and Callahan, 2013). Soybean, canola, sunflower seed, flax seed, safflower seed are the common oilseeds for on-farm plant oil production by mechanical pressing.

Increasing profits and reducing the oil production cost are the main motivations for on-farm oil productions. Simple facilities are required on farms to produce plant oils and other value-added products. Farmers can sell oil products or use them as fuel to power farming facilities such as tractors or combines. Additionally, the co-products produced from the pressing process are used as animal feed. The result is a well-integrated system where in addition to commodity crops, farmers produce fuel and animal feed as well.

On-farm processing includes oilseed harvest, cleaning, pressing, and other processes depending on the end-product (Grubinger, 2007). The oilseed cleaning ensures high-quality oil and longer seed storage. The cold-pressing with screw presses is generally used for on-farm oil production (Darby and Callahan, 2015). Before pressing, the moisture content of oilseed is controlled to 6–9% for improving flowability through the presses (Grubinger, 2007). Capacities of on-farm facility range from 0.5 tonne to 6 tonne of oilseeds per day generally, and the oil productivity ranges from 11 L/hr to 15 L/hr depending on feedstock (Grubinger, 2007; Darby and Callahan, 2015). Post processing steps depend on whether the oil is to be used for food or fuel. Mostly, on-farm plant oil is used to produce biodiesel (Grubinger, 2007; Fore et al., 2011; Darby and Callahan, 2015). The pressed cake is usually fed to livestock.

3.3. Fixed capital investment

3.3.1. Fixed capital investment of on-farm oil production

For mechanical oil pressing, the major components are a seeds cleaner, presser or expeller, and oil filter. Table 1 lists the fixed capital investment for on-farm and small-scale plant oil production by mechanical pressing.

Helgeson and Schaffner (1983) investigated on-farm production of sunflower oil at three capacities and observed that the oil presser is the major fixed cost (> 24% of the total fixed cost) followed by oil filter and oil storage facilities. As the production capacity increases, the cost of the presser cost increases to 35% of the total fixed cost. Additionally, they reported that a 0.13 power relationship between the total fixed cost and the plant capacity ratio exists for different capacities. Grubinger (2007) evaluated an on-farm sunflower and canola oil production system and estimated that the unit fixed cost was 5 cents/kg oilseed, and the oil presser and the oil storage tank account for one-third of total fixed costs. White and Callahan (2013) reported that for on-farm sunflower oil production in Vermont, and the breakeven annual operation capacity was 128 tonnes of oil seeds with a unit fixed cost of \$0.29/kg oilseeds.

Fore et al. (2011) studied canola oil and soybean oil on-farm productions with either low, medium or high capitalization, at the same oil

Table 1
The fixed cost of on-farm plant oil production.

	Feedstock	Scale (tonne/yr)	Fixed cost (\$)	Unit cost (\$/kg feedstock)	Lang factor
Helgeson and Schaffner (1983)	Sunflower	105	78125	0.74	1.63
		501	85455	0.17	1.55
		1500	112064	0.08	1.46
Grubinger (2007) Fore et al. (2011)	Sunflower/Canola	720	35400	0.05	N/A
	Canola	480	low: 6018 medium: 18054 high: 51566	low: 0.01 medium: 0.04 high: 0.11	N/A
Fore et al. (2011)	Soybean	667	low: 6018 medium: 18054 high: 51566	low: 0.01 medium: 0.03 high: 0.08	N/A
White and Callahan (2013)	Sunflower	128	36750	0.29	N/A
Illupitiya and de koff. (2014)	Oilseeds	800 kg/batch	10504	N/A	N/A
Mupondwa et al. (2016) ^a	Camelina	30000	12538190	0.42	2.38
		60000	16715870	0.28	2.68
		120000	25266930	0.21	3.02

^a Canadian case.

productivity. The high and the low capitalization levels indicate the perceived upper and lower bound to potential costs, and the medium level depicts the average scenarios. The unit fixed cost ranges from 1¢/kg seed to 11¢/kg seed for pressing canola and 1¢/kg seed to 8¢/kg seed for soybeans. The unit fixed cost of pressing soybeans is lower than for canola seeds because soybeans had a lower oil content (18% db) compared to canola seeds (38% db). More soybeans are needed to have the same oil productivity as canola. Additionally, the cost of the oil press accounts for over 95% of the total fixed costs in the low capitalization scenario. For the high capitalization scenario, it is about 42% of total fixed costs because more equipment installation is required to have a complete operation, such as conditioning, oil filtering, and oil storage.

In a Canadian study on camelina oil production (Mupondwa et al., 2016), the unit fixed cost ranged from 0.21 to 0.42 \$/kg oilseeds for larger-scale operations. Fixed costs scale with production capacities has a 0.34 power relationship. Mupondwa et al. (2016) reported the Lang factor for the fixed capital investment is from 1.4 to 3.02 and varies with the location of the plant and economic-related factors. For facilities located in the U.S., the lower Lang factor value was observed (Helgeson and Schaffner, 1983).

3.3.2. Fixed capital investment of oil pressing in industrial operations

The application of mechanical pressing for industrial operations is typically used for producing high nutrition livestock feeds with higher value. Table 2 lists the fixed capital investment of the industrial scale of mechanical pressing which includes soybean oil production, oil extraction from lipidcane, and jatropha oil production.

In a commercial soybean crushing plant, controls and instruments constitute 5–25% of the total equipment costs which greatly affect operating expenses, efficiency, and product quality. Additionally, a 0.75 ± 0.05 power relationship was applied to estimate total facility costs for different capacities in industrial operations (Fiala, 1995). For soybean oil production, Cheng (2017a,b,c) investigated the costs of soybean pressing according to a Landus Cooperative plant in Ralston, IA at six production capacities. The unit fixed cost ranges from 0.06 to 0.89 \$/kg soybean, and a 0.42 power relationship was needed to estimate fixed costs. Huang et al. (2016) performed the study on the costs of biofuel production from the lipidcane. The oil content of lipidcane varied from 2% to 20%. The unit fixed cost ranges from 2.8 to 3.4 ¢/kg feedstock based on oil productivity. The lipidcane with higher oil content needs higher fixed costs, especially for oil extraction, purification, storage, and utility-related facilities. For utility-related facilities and storage costs, an increase of 59% and 53%, respectively were observed when high oil content lipidcane was processed. The cost of extraction and purification increases by 12% when lipidcane with

Table 2
The fixed cost of industrial scale plant oil production.

	Feedstock	Scale (1000 tonne)	Fixed cost (million \$)	Unit cost (\$/kg feedstock)	Lang factor
Huang et al. (2016)	Lipidcane	1600	20%: 53.26	0.034	3
			10%: 49.61	0.031	
			5%: 47.30	0.029	
			2%: 45.32	0.028	
Cheng (2017a,b,c)	Soybean	30.77	27.37	0.89	2.43
			96.14	0.45	
			192.28	0.33	
			672.99	0.17	
			1527.53	0.13	
Wang (2016) ^a Navarro-Pineda et al. (2017) ⁺	Jatropha	840	164.86	0.06	1.65
			67.33	0.08	
			\$38045	0.01	
	Jatropha	7.92			N/A

^a Taiwanese case; +: Mexican case; Oil extracted from lipidcane and jatropha are not commercially available, the cost reported here are estimated values based on published studies.

higher oil content was processed.

The lower unit fixed cost, 1 ¢/kg oilseed (Navarro-Pineda et al., 2017) and 8 ¢/kg oilseed (Wang, 2016) were observed for jatropha oil production in Mexico and Taiwan, respectively compared to 0.1 to 1.0 \$/kg oilseed in the U.S. Additionally, the Lang factor of Wang's study (2016) is 1.65, which is close to the on-farm oil production in the US. From this aspect, the variances of the fixed costs might be related to different plant locations and equipment suppliers (Peters et al., 2003).

3.4. Production costs

3.4.1. On-farm plant oil production costs

The motivation for producing plant oil on-farm is the low cost of oilseeds. On-farm oil production has 10–29% lower material costs because the oilseeds are produced on the farm and there are savings related to transportation and other related costs (Fore et al., 2011). Table 3 shows the production costs of on-farm plant oil production.

Helgeson and Schaffner (1983) compared three different capacities, 0.35, 1.67, and 5 tonnes of oilseeds annually for producing sunflower oil. The unit production cost were 0.35, 0.27, and 0.30 \$/kg oil, respectively. Unit production cost fell with increased capacity. Material cost is a big portion of total production costs. Though the oilseeds are produced on the farm, the oilseed costs mainly come from planting and harvesting. Additionally, the oilseed meal was sold as livestock feeds

Table 3
The production costs of on-farm oil production.

	Feedstock	Scale (tonne oil/yr)	Production cost (\$)	Unit cost (\$/kg oil)	Credit (\$/kg oil)
Helgeson and Schaffner (1983)	Sunflower	163.2	low: 56543	0.35	0.065
			medium: 45760	0.27	0.057
			high: 46400	0.30	0.057
Grubinger (2007)	Sunflower/Canola	248.28	233720	0.94	0.66
	Canola	22.5	low: 28346	low: 1.26	0.53
Fore et al. (2011)	Soybean	22.5	medium: 29260	medium: 1.25	
			high: 27551	high: 1.23	
			low: 41062	low: 1.83	1.38
White and Callahan (2013)	Sunflower	13.6	medium: 40796	medium: 1.82	
			high: 40000	high: 1.78	
			31250	2.30	0.72
Mupondwa et al. (2016) ^a	Camelina	9120	94440	2.14	0.67
			23529600	2.58	0.53
Nevase et al. (2012) ⁺	Jatropha	86.4	36480000	1.00	0.51
			57260	0.66	0.12

^a Canadian case; +: Indian case; Oil extracted from lipidcane and jatropha are not commercially available, the cost reported here are estimated values based on published studies.

Table 4
The production costs of the industrial scale plant oil production.

	Feedstock	Scale (1000 tonne oil)	Production cost (million \$)	Unit cost (\$/kg oil)	Credit (\$/kg oil)
Huang et al. (2016)	Lipidcane	86.4	73.5	0.85	0.29
		43.2	73.5	1.70	0.36
Cheng (2017a,b,c)	Soybean	4.1	21.63	5.27	3.93
		12.81	58.15	4.54	
		25.62	111.69	4.36	
		89.67	368.94	4.11	
		167.56	679.44	4.06	
Wang (2016) ^a	Jatropha	398.67	1561.24	3.91	
		221.76	124.12	0.89	0.41

^a Taiwanese case; Oil extracted from lipidcane and jatropha are not commercially available, the cost reported here are estimated values based on published studies.

and considered as credits to the oil production process. The net unit production costs were 0.24–0.29 \$/kg oil. White and Callahan (2013) investigated smaller scaled sunflower oil on-farm operations. The unit production costs are 2.30 \$/kg oil and 2.14 \$/kg oil of 13.6 tonnes and 44.2 tonnes of annual oil productions individually. Their net production costs are 1.58 \$/kg oil and 1.47 \$/kg oil.

In a study by Grubinger (2007), the unit production cost is 0.94 \$/kg oil with a credit from the meal of 0.66 \$/kg oil. Hence, the net production cost is 0.28 \$/kg. According to Fore et al.'s study (2011), the production cost varies with capitalization because that affects labor and utility costs. The production cost decreases when more is spent on equipment because of more efficient processing and higher oil yields. In the cases of low, medium, and high capitalization, the unit production costs of canola oil are 1.26 \$/kg oil, 1.25 \$/kg oil, and 1.23 \$/kg, respectively. When co-product credit for the meal (0.53 \$/kg oil) is considered in these cost estimates, the net unit production costs decreases to 0.73 \$/kg oil, 0.72 \$/kg oil and 0.70 \$/kg oil, respectively. For soybean oil, higher unit production costs, 1.83 \$/kg oil, 1.82 \$/kg oil and 1.78 \$/kg oil, are observed because of soybeans lower oil content. However, soybean meal has a higher feed value than canola meal. The net production cost estimate shows that soybeans are less expensive to process than canola seeds at 0.45 \$/kg oil, 0.44 \$/kg oil, and 0.40 \$/kg oil at the three levels of capitalization, respectively. In terms of production expenses, oilseed costs account for over 85% (for either soybean or canola) followed by electricity cost (5.20–7.25%) and labor cost (3.23–7.19%).

Mupondwa et al. (2016) analyzed camelina oil production in

Canada at both 9120 and 36480 tonne/yr. The unit production costs are 2.58 \$/kg oil and 1.00 \$/kg oil, and their net production costs are 2.05 \$/kg oil and 0.49 \$/kg oil, respectively. Though the result is close to the production cost of sunflower oil reported by White and Callahan (2013), the production capacity (e.g. scaling) is much larger. Hence, it is difficult to compare the cost differences from different feedstocks and plant locations based on comparable bases.

The cost analysis of small-scale jatropha oil production for biodiesel was performed by Nevase et al. (2012). The unit production cost was estimated to be 0.66 \$/kg oil. However, the jatropha meal cannot be used as animal feeds. A credit was given for glycerol (0.12\$/kg oil). Hence, the net unit production cost is 0.54 \$/kg oil, which is close to the unit production cost of canola oil and soybean oil reported by Fore et al. (2011).

3.4.2. Production costs of the mechanical press in industrial operations

At the industrial scale, mechanical pressing is selected for specific applications, such as livestock feed productions, food applications, and nutrition supplement productions. The plant oil production cost of the industrial mechanical pressing process is summarized in Table 4.

According to Cheng's study (2017^a), the unit production cost of soybean oil production varies from 5.27 \$/kg oil to 3.91\$/kg oil when the capacity is scaled up. A -0.07 power relationship was reported to estimate the unit production cost. Material cost accounts for the largest portion of the all production costs ranging from 64 to 86% as capacity increases. Utility cost is the next largest expense. It increases from 8.3 to 12% when the capacity is scaled up because more energy is required to power the equipment in a larger production facility. Additionally, the credits derived from soybean meal were estimated at 3.93 \$/kg oil. Hence, the net unit production costs ranged from 1.34 \$/kg oil to -0.02 \$/kg oil when the capacity increases. Here, the negative value indicates the credits from the meal covers all expenses spent on oil production. This would suggest that the mechanically pressed meal is the major product of the process rather than soybean oil. Additionally, the selling price of mechanically pressed soybean meal is \$0.17/kg higher than the solvent extracted meal which makes mechanical pressing process an economically viable process for industrial applications (Cheng, 2017a).

Huang et al. (2016) investigated the production cost of oil production from the transgenic lipidcane. Lipidcane with 20% and 10% oil content were analyzed. Because the pressing capacity was set at 1600 thousand tonnes of annual feedstock handling, the total production cost was assumed to be the same for the different lipidcane oil contents. The higher oil content lipidcane has a lower unit production cost (0.85 \$/kg oil) than that of the lower oil content lipidcane (1.70 \$/kg oil). In this study, oil was used for biodiesel production and

bagasse for cellulosic ethanol production. Hence, the credits were calculated according to revenues from glycerol and ethanol, which are 0.29 \$/kg oil (20% lipidcane) and 0.36 \$/kg oil (10% lipidcane). The net unit production costs were estimated as 0.56 \$/kg oil and 1.34 \$/kg oil. Similar to soybean oil production, lipidcane accounted for > 85% of the total production costs.

Wang (2016) performed the cost analysis of using jatropha oil for jet fuel production. In the oil extraction part, the unit production cost is 0.89 \$/kg oil. The extracted seeds were burned to produce biochar and bio-oil. The net unit production cost was estimated at 0.48 \$/kg oil.

4. Solvent extraction

4.1. Solvent extraction process

In the U.S., plant oil produced from the solvent extraction accounts for over 95% of the total plant oil production due to its high oil yield and energy efficiency (US EPA, 2001; Anderson, 2011). Commercial (or extraction) hexane is typically used for oil extraction. It consists of a mixture of hexane isomers, and has a similar specific gravity to *n*-hexane. But, it has a slightly greater ability to extract oil from oilseeds, a higher ignition (264 °C versus 225 °C) and flash temperature (−18 °C versus −26 °C), and approximately 10 °C lower boiling temperature. These properties make extraction hexane safer for use in industrial operations than pure *n*-hexane (Anderson, 2011; Cheng, 2017b).

The process of solvent extraction used with most oilseeds is illustrated in Fig. 4. Similar to the mechanical pressing process, oilseeds are cleaned to remove foreign matters followed by drying and conditioning to achieve 10% moisture content. Cracking and dehulling are performed to remove hulls, which are sold as livestock feeds, by a cracker and aspirator, respectively. After the dehulling process, the cracked seeds are heated to 71 °C, and the moisture content is conditioned to 11% by steam or water spray. This step prepares the cracked seeds for the flaking process. Flaking increases the surface area of oilseeds to improve extraction efficiency (Woerfel, 1995; Anderson, 2011; Cheng, 2017b).

In the extraction process, the ratio of solvent to oilseed is 5–10 for the typical immersion approach. These large amounts of solvent usage create issues related to safety, environmental impact, and high solvent cost. The countercurrent percolation technique was introduced to

reduce solvent usage (1:1 solvent to solid ration) and maintain an oil recovery of over 95% (Pramparo et al., 2002). In the industry, continuous loop extractor (Crown Iron Works, 2016), belt extractor (Extraction de Smet, 2016), and rotary Rotocel[®] reactor (Becker, 1978) are the three major types of extractors for plant oil extraction (Cheng, 2017b). The desolvenization is performed after the extraction, and the solvent is recycled and reused. Steam and vacuum are applied in the desolvenization process. The steam of 121 °C contacts with extracted oil briefly to avoid oil deterioration. After desolvenization, the residual solvent in the crude oil is removed to below 1000 ppm (Proctor, 1997).

After the oil is extracted, a toaster is used to remove solvent present in the cake. Steam is used to evaporate the solvent and produce oilseed meal, which is favored as livestock feed because of its high protein content. During the toasting process, steam also heats the meal up to 100–105 °C enhancing the anti-nutritional value by inactivating anti-nutritional agents such as trypsin inhibitors in soybean meal. The meal is dried to 10% moisture before being shipped to market (Hettiarachchy and Kalapathy, 1997; Cheng, 2017b).

4.2. Fixed capital investment of the solvent extraction

Extracting oil with solvent is much more complex than mechanical pressing. More operations are required, such as desolvenization, solvent recycling, and waste stream handling. Though solvent extraction is used to produce the vast majority of plant oil, its cost of production has not been extensively reported. The oil extraction process was excluded in some of the published techno-economic analyses of oil refinery or oleochemical production; where, the price of plant oil was set directly (Haas et al., 2006; Ngo et al., 2012). Table 5 lists the fixed capital investment of solvent extraction process extracted from published techno-economic studies on plant oil applications (Marouli and Maroulis, 2005; Vlysidis et al., 2011; Cheng and Rosentrater, 2017).

Marouli and Maroulis (2005) reported the fixed cost for hexane extraction of crude soybean oil marketed to the food industry. In a plant handling 1755 million tonnes of soybean annually, the total fixed capital investment was estimated at \$54 million, and the unit fixed cost is 0.32 \$/kg oilseed. The Lang factor of 4.21 was reported for estimating the total fixed cost. Cheng and Rosentrater (2017) investigated six capacities to produce the degummed crude soybean oil by hexane extraction. The fixed cost ranges from \$42 to 204 million, and 0.34 power relationship was reported to estimate the total fixed cost for different operation capacities. Additionally, the Lang factor of 4.01 was reported to estimate total plant cost based on equipment purchasing costs.

Vlysidis et al. (2011) performed the techno-economic study on biodiesel production from rapeseed oil. The solvent extraction was included in the simulation model. In a 1940 tonnes annual oilseeds process, oil extraction accounts for 39% of the total fixed cost of the biodiesel plant. The unit fixed cost of the oil extraction was estimated at 0.36 \$/kg oilseed. Additionally, the Lang factor of 4.18 was reported to estimate the total fixed cost based upon equipment costs.

The lowest unit fixed cost was reported by Abhyuday Techno Economic Consultants (ATECC, 2017). It was estimated to be 4 ¢/kg oilseed for an industrial operation processing 77500 tonnes of oilseed annually. The result also demonstrates the importance of location in determining fixed costs.

4.3. Production costs of the solvent extraction

Table 6 shows the production cost of plant oils other than soybean oil (Gatewood, 2013). The combination of mechanical pre-pressing and solvent extraction is used to produce oils when the oilseeds have the oil content higher than 30% (Anderson, 2011). Therefore, unit price varies among oilseeds because of required process modifications and different co-products (Gatewood, 2013).

There is more data available for soybeans than other oilseeds, likely because soybean is the dominant oilseed crop in the U.S. Soybean oil

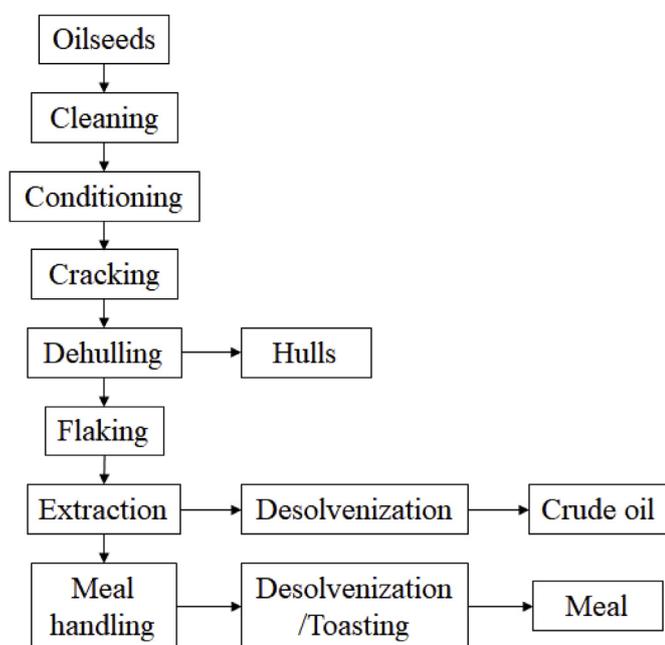


Fig. 4. The process of oil solvent extraction.

Table 5
The capital investment of plant oil production by hexane extraction.

	Feedstock	Scale (1000 tonne/yr)	Fixed cost (million \$)	Unit cost (\$/kg feedstock)	Lang factor
Marouli and Maroulis (2005) Cheng and Rosentrater (2017)	Soybean	1754.4	53.78	0.32	4.21
	Soybean	22.43	42.23	1.88	4.01
		67.30	47.74	0.71	
		192.28	85.24	0.44	
		408.71	101.19	0.25	
		961.42	131.54	0.13	
		2307.4	203.55	0.09	
Vlysidis et al. (2011) ^a ATECC (2017) ⁺	Rapeseed	1.94	7.00	0.36	4.18
	Oil seeds	77.5	2.85	0.04	N/A

^a UK case; +: Indian case.

Table 6
The production costs of commercial plant oils (Gatewood, 2013).

	Unit cost (\$/kg)
Canola	2.78
Peanut	5.44
Sesame	16.83
Other oil crops	3.43

production costs are listed in Table 7. Marouli & Maroulis study (2005) reported the unit production cost as 0.56 \$/kg oil for a plant producing 0.3 million tonnes of soybean oil annually. The cost for materials accounts for 92% of the total production costs followed by that of utilities (5%). The labor cost and other supplementary costs account for 1.39% and 1.31% of the total production costs, respectively. Low labor and supplementary costs indicate the solvent extraction is a more efficient process than the mechanical pressing.

From Cheng and Rosentrater's study (2017), the unit production cost ranges from 2.69 \$/kg oil to 5.74 \$/kg oil, and increases with plant capacity. A -0.15 power relationship estimated the total production cost for different production capacities. The cost of material accounts for most of the total production cost (44%–94%) followed by facility-related and utility costs; where, facility-related cost includes equipment maintenance and supplementary costs. In contrast to material cost, the facility-related and utility costs decrease as the production capacity increases. This suggests that hexane extraction is a highly capitalized and efficient process. Additionally, soybean hull and soybean meal are two co-products. When considering them as credits, the net unit production costs range from 0.73 \$/kg oil to 3.78 \$/kg oil.

You et al. (2008) performed a techno-economic analysis of biodiesel production using soybean oil. The unit production cost ranged from 0.65 to 0.70 \$/kg oil. A -0.03 power relationship estimated the production cost for different production capacities. Material cost is still the major portion of the total production cost which increases from 64.8% to 75.9% when the plant is scaled up. In this study, char and glycerol

Table 7
The production costs of plant oil production by hexane extraction.

	Feedstock	Scale (1000 tonne oil/yr)	Production cost (million \$)	Unit cost (\$/kg oil)	Credit (\$/kg oil)
Marouli and Maroulis (2005) Cheng and Rosentrater (2017)	Soybean	300	168.05	0.56	N/A
	Soybean	4.04	23.19	5.74	1.96
		12.12	42.32	3.49	
		64.64	108.34	3.13	
		86.61	246.07	2.84	
		173.22	475.63	2.75	
		415.73	1116.66	2.69	
You et al. (2008) [▲]	Soybean	8	5.67	0.70	0.35
		30	20.06	0.69	0.33
		100	65.29	0.65	0.32

▲: Taiwanese case.

were considered as co-products. Net production costs were 0.33–0.36 \$/kg oil.

In the studies summarized above, feedstock cost is the most important factor in determining total production costs. The remaining cost factors are labor, utilities, and miscellaneous costs. These results show the hexane extraction process to be a highly capitalized, efficient and favored process for plant oil production in the industry compared to the mechanical pressing process.

5. Comparison of costs for plant oil production using the three processing technologies

5.1. Fixed capital investment

The fixed capital investment is determined from the equipment purchasing price multiplied by the Lang factor. Table 8 shows the Lang factor ranges for on-farm oil production, mechanical pressing in industrial applications, and the solvent extraction plant. The Lang factor increases with the complexity of the process, which is why it is much larger when using solvent than mechanical pressing for extraction.

For solvent extraction, more instrumentation and higher installation fees are required, such as insulation, piping, and other auxiliary expenses, due to the use of a flammable organic solvent, need for solvent recycling, and a generally complex process. In contrast, mechanical pressing is relatively straightforward. The main equipment used to extract oil is a press or an expeller; hence, less instrumentation is required and it is easier to install. Interestingly on-farm oil production and industrial mechanical pressing systems have similar Lang factors.

The unit fixed costs for plant oil production using all three methods are illustrated in Fig. 5. As for the solvent extraction process, the capacities larger than 67 thousand tonnes of annual oilseeds processing have positive net profits (Cheng and Rosentrater, 2017). These processes with positive net profit were used to have an average unit fixed cost of each processing technology.

Solvent extraction process has the highest unit fixed cost which is \$0.32/kg oilseed. For solvent extraction process, high facilities costs are

Table 8

Lang factor used for estimating the fixed capital investment of plant oil production plants.

	Lang factor	Process complexity
On-farm oil production	1.46–3.02	Low
Mechanical pressing	1.65–2.26	Low to medium
Solvent extraction	4.01–4.21	High

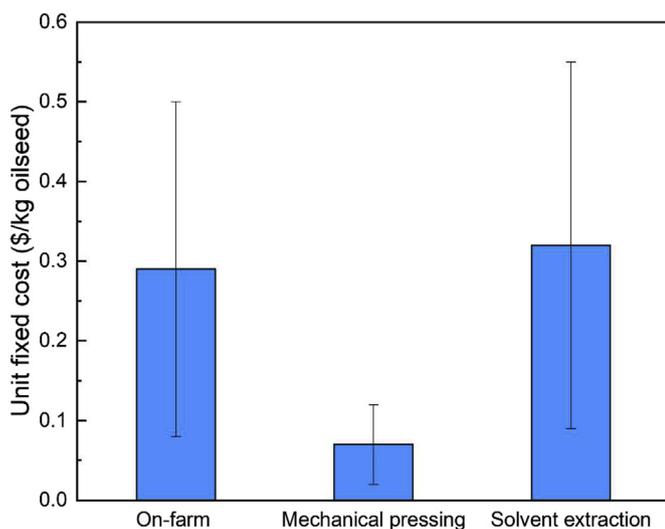


Fig. 5. Unit fixed cost of plant oil productions.

required because it is a more capitalized and complex process. Interestingly, on-farm oil pressing process has a similar unit fixed cost (\$0.29/kg oilseed) to the solvent extraction process. It is because on-farm oil pressing is at very small scale and does not benefit from the savings afforded by larger operations. Industrial mechanical pressing process has the lowest fixed cost (7 ¢/kg oilseed) among these three plant oil production processes because it combines the merits of relatively low capitalization and large scale.

The large variances among models for the same process can be accounted for by plant locations, equipment suppliers, simulation assumptions and a variety of other factors (Fore et al., 2011).

5.2. Production costs

The unit production costs of on-farm, industrial pressing, and solvent extraction are compared for total and net unit costs (Fig. 6). Net unit costs take into account co-product credits. Industrial mechanical pressing process has the highest unit production cost (3.60 \$/kg oil) followed by solvent extraction (3.06 \$/kg oil) and on-farm oil production (1.36 \$/kg oil). The lower oil recovery efficiency of mechanical pressing (70–80%) compared to solvent extraction (> 95%) results in higher unit production costs. It seems counter intuitive as to why the on-farm system, scaled so much smaller, should produce oil at lower cost compared to large scale industrial facilities. For on-farm systems, inefficiencies from size are more than made up with access to less expensive oilseeds. Fore et al. (2011) estimated that the oilseed cost associated with on-farm systems is 10%–29% less than purchasing it from the market. Therefore, the production cost of the on-farm oil process is 15–43% lower than the industrial pressing operation.

When the credits derived from the co-products are considered, the industrial mechanical pressing has the lowest net unit production cost (0.57 \$/kg oil) followed by on-farm oil production (0.72 \$/kg oil) and solvent extraction process (1.48 \$/kg oil). The press cake has a higher selling price than solvent extracted meal due to its higher energy content and nutritional value.

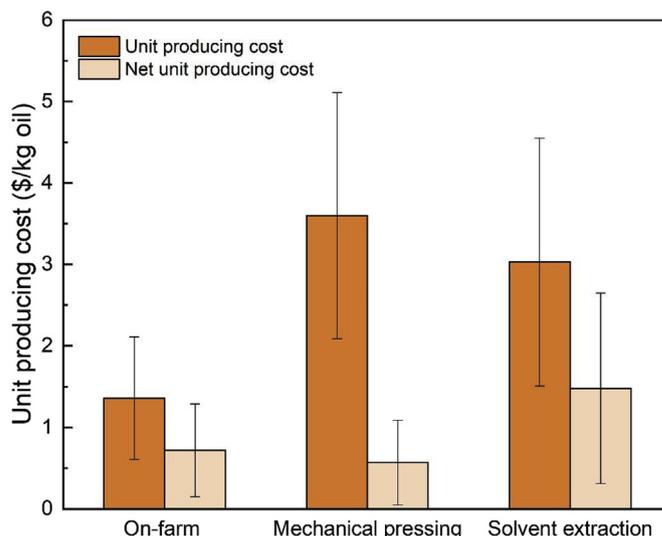


Fig. 6. Unit production cost of plant oil productions.

6. Future perspective

Oil recovery and solvent usage are primary concerns for plant oil industry which significantly affect the oil production costs. Non-solvent oil extraction, such as aqueous extraction, is becoming more attractive for industrial applications because it is greener, safer for operation and more eco-friendly.

Aqueous extraction using water as the solvent was introduced in the 1950s for various oilseeds (Johnson and Lucas, 1983; Rosenthal et al., 1996). The oil recovery can reach over 90% from aqueous extraction by adding flaking and extruding as pretreatments and assisted by protease (Jung et al., 2009; de Moura et al., 2011). Cheng (2017c) performed the cost analysis of aqueous extraction in an industrial application based on de Moura et al.'s study (2011). The breakeven capacity was 17 million kg of annual soybean oil production with the net unit production cost of \$2.6/kg oil. However, wasted water and enzyme recycles are required to reduce material expenses. Enzymatic assisted aqueous extraction process (EAEP) is a potential alternative for industrial applications.

Additionally, oil extraction from stillage in corn dry-grind ethanol plant has become popular in last 10–15 years. The corn distillers' oil production reached over 1.8 million tonnes in 2017 (USDA NASS, 2018). Typically, heat and centrifugation are used to separate oil from stillage after fermentation. Corn distillers oil is primarily used as an ingredient in animal diets and for making biodiesel. For reducing energy consumption and improving oil recovery, the aqueous extraction was also proposed for distillers oil production by using enzymes or adjusting pH value to increase the total profit of the corn dry-grind ethanol plant (Majoni et al., 2011; Dickey et al., 2011; Moreau et al., 2014).

Furthermore, it is worth investigating the credits from co-products which could significantly improve the feasibility of solvent-free technology used in plant oleochemical industry.

7. Conclusion

Crude plant oil is extracted from oilseeds either by extracting with commercial hexane or mechanical pressing. Mechanical extraction of oil is a more straightforward process compared to solvent extraction because it is solvent-free and does not need as much upfront seed preparation. For this reason, the mechanical process can be operated at a wide scale range; from on-farm to industrial scale. However, mechanical pressing is less efficient in oil recovery than with the solvent process. Overall, the following notable trends were noticed:

- Unit fixed costs are similar for the solvent and on-farm processes and much less for the commercial scaled mechanical process.
- Unit oil prices are ranked: industrial scaled press system > solvent-based system > on-farm system. Savings for on-farm systems arise from access to discounted oilseed.
- Net unit oil prices are ranked: industrial scaled press system > on-farm system > solvent system. Mechanical system benefits from the higher quality of the press cake versus the meal for soybeans.

Studies of similar extraction methods varied widely in their final cost estimates, which indicates the importance of geographical location and other factors in dictating the optimal process.

Acknowledgment

This work was funded by the DOE Center for Advanced Bioenergy and Bioproducts Innovation (U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research under Award Number DE-SC0018420). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the U.S. Department of Energy.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.bcab.2019.101056>.

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