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Investigating the Efficiency of Canola and Corn Oil Used for Potato Chip Frying at Frito-Lay

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Abstract

In 2014, Frito-Lay held 60% of the potato chip market share in the United States, generating over $3 billion in sales (PepsiCo Annual Report, 2017). The company uses canola and corn oil to fry the potatoes. Frito-Lay operators noticed that a greater amount of canola oil is required to produce one pound of potato chips than corn oil. Our project aims to determine the cause of the difference in oil efficiency observed when using canola oil and corn oil to fry potato chips. We conducted pilot and plant scale experiments, analyzed Frito-Lay’s quality control data and evaluated the equation used to calculate oil efficiency. It was found that canola’s absorption in the potato chips is higher than corn by 3% to 5% approximately.

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Acknowledgements

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Introduction

In 2017, 277 million Americans consumed potato chips making it one of the most popular snack foods in the United States (Statista, 2017). Their popularity continues to grow as increasingly busy lifestyles lead people to shift from elaborate meals to snacks (Research and Markets, 2017). By the end of 2016, the market value of potato chips in the United States was at $26 billion and is expected to grow to $40.3 billion by 2022 (Research and Markets, 2017).

Frito-Lay is the largest manufacturer of potato chips market in the United States (Forbes, 2017). Currently, Frito-Lay has a brand value of $13.6 billion (Forbes, 2017). The company was founded in 1961, and later merged with PepsiCola to form PepsiCo. According to PepsiCo's 2016 Annual Report, 25% of the total revenue was generated by Frito-Lay. The company manufactures snack foods such as Lay's potato chips, Doritos tortilla chips and Cheetos snacks. In total, there are over 1,100 different Frito-Lay products manufactured in over 30 facilities in the United States.

When frying potato chips, Frito-Lay uses corn oil, canola oil or a 60%-40% corn-canola blend. A discrepancy exists among the oil efficiencies when potatoes are fried with the different oils. Our project aims to evaluate the difference in oil efficiency when canola oil and corn oil is used to fry potato chips. Frito-Lay operators have observed that a greater amount of canola oil is required to produce the same amount of product than when pure corn oil is used. The difference in oil efficiency is thought to be attributed to a difference in physical properties and chemical behavior of the two oils during frying. Knowing what factors cause this discrepancy would allow Frito-Lay to improve their chip production at the Killingly, Connecticut plant and, ultimately in other plants.

Background

An overview of the frying process at Frito-Lay, the chemical reactions during frying, and the mass balance of this system will be discussed in this section.

Potato Chip Production at Frito-Lay

The potato chip frying process at Frito-Lay is a continuous process. The process is completely automated and uses a conveyor belt system to move the potato chips through various stages of production. When the potatoes arrive at the facility, samples are taken to ensure that the potatoes meet quality standards. Additional tests are also performed to measure the solid content of the potatoes. The potatoes are then peeled and sliced to different thicknesses based on product type, usually ranging from 0.05 inches to 0.1 inches. Subsequently, the potato slices go through a cleaning system and are transported into the chip fryer. They are dried by a blower with hot air to remove excess moisture before they enter the fryer.

Frito-Lay uses corn oil, canola oil and a 60% to 40% by volume blend of corn and canola to fry their chips. Once inside the fryer, the average residence time of a potato chip is three minutes. The Killingly manufacturing plant has two continuous chip fryers with paddles that move the oil and the potatoes through the vessel. The temperature of the oil inside the chip fryer is monitored and maintained at 360˚F. Temperature is an important factor in chip frying, as too high of a temperature may cause the oil to go rancid faster or may cause the chip to burn (NOEDA, 2013). Conversely, too low of a temperature may result in an excessive absorption of fat by the food (NOEDA, 2013). As the potato chips exit the fryer, an infrared light system detects and records the moisture content and the oil absorbed by the chips. Frito-Lay aims for an oil content of 35% in their potato chips. Finally, the potatoes are seasoned depending on the product being produced and sent to packaging.

Production of Canola and Corn Oil

Canola and Corn oil are common cooking oils used for frying. Canola oil is the edible component of rapeseed oil. The oil is extracted from canola seeds that contain 38-44% oil. The most common extraction method involves mechanically pressing the seed, which extracts about

60% of the oil. The extraction process involves seed cleaning, heating to about 30 to 40 ^{o}C, flaking, pressing and then extraction. During flaking, the cell walls in the seeds are destroyed and some of the oil can begin to be collected. Pressing is where most of the oil is collected.

Corn oil is extracted from one part of the corn kernel known as the germ. Industries commonly use #2 yellow dent corn. The oil extracted from corn represents only 4% of the whole corn structure. The first step in extraction is steeping, in which corn is soaked in water for about 30 to 40 hours at 50 ^{o}C to soften the corn. The germ is put into cyclone separators and washed to eliminate any lingering starch. Then, the oil is extracted from the germ by using solvents and then filtered to produce the finished corn oil.

Chemical Reactions during Frying

Potatoes are comprised of 75% water and 25% solids. During the process of frying, a large portion of the potato’s water vaporizes due to the high temperature of the oil, essentially dehydrating the potato. The high temperature and low moisture during frying causes color development, or browning of the potato. While frying, oil is absorbed and water is replaced simultaneously. Initially, only the surface moisture of the potato evaporates, leading to the formation of the chip crust (Ziaiifar, 2008). When all the surface moisture is evaporated, the water inside the potato begins to evaporate, leaving pores for the oil to occupy. The water that evaporates creates a steam blanket above the oil. The steam blanket is important in ensuring oil quality as it “reduces the contact between the oil and oxygen, and lowers the rate of oxidation” (Blumenthal 1991). As the frying process approaches completion, both the water vapor loss and oil intake slow down. When frying is completed, the remaining voids inside the potato are filled by surface oil as the potato cools (Pedreschi & Moyano, 2005).

Hydrolysis

The water released from potatoes during frying reacts with the hot oil in a hydrolysis reaction. Frying oils are composed of 91% to 99% triglycerides, depending on the kind of oil (Przybylski, n.d.). Triglycerides are composed of one ester molecule and three fatty acids. During hydrolysis, water attacks the ester linkage of the triglycerides in oil, forming di- and mono- acylglycerides, glycerol and free fatty acids. Particularly of interest to the quality of oil is the free fatty acid (FFA) content. Free fatty acids result in the off flavor of oil, and oxidize more easily than triglycerides. To assure quality standards are met, the free fatty acid content should be kept below 0.05-0.08% (Stevenson et al., 1984). Shown in Figure 1 below is a representation of the chemical compounds involved in the hydrolysis reaction.

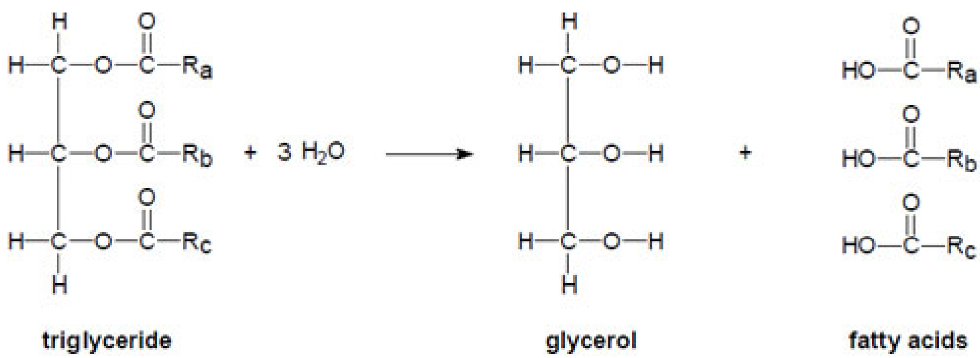


Figure 1: Hydrolysis of Frying Oil

Oxidation

Oxidation is another chemical reaction that occurs during frying. As a result of the air present inside the chip fryer, the free fatty acids formed during hydrolysis oxidize via a free radical mechanism in three steps: initiation, propagation and termination. In the initiation step, a radical that reacts with oxygen is formed (Perkins, 1992). The propagation step involves the formation of hydroperoxides. Lastly, the termination step produces volatile and nonvolatile compounds (Choe and Min, 2007). Figure 2 below shows the detailed mechanism of the oxidation reaction.

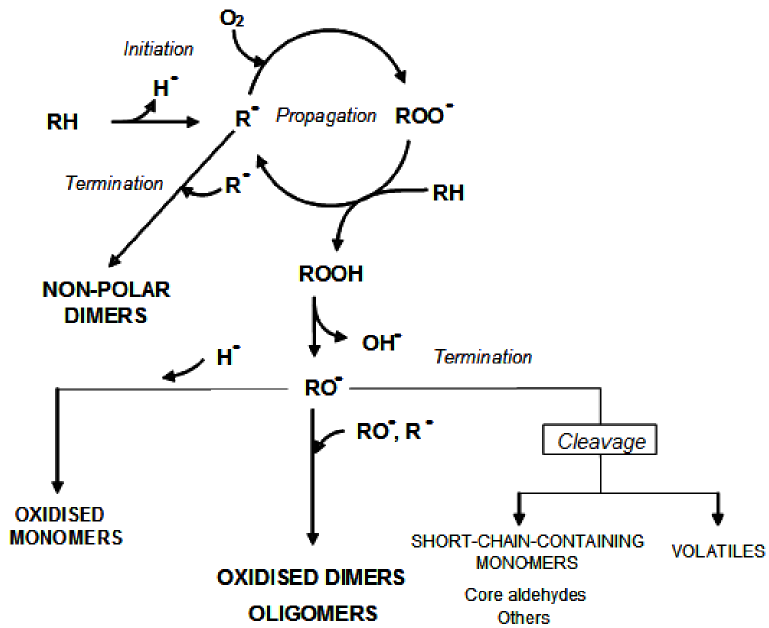


Figure 2: Mechanism of the Oxidation of Oil (Perkins, 1992)

The quantity of unsaturated fatty acids affect the oxidation rate of oil. Table 1 below shows the fatty acid composition of canola and corn oil. The oxidation rate is higher in oils with a higher amount of unsaturated fatty acids, since they contain double bonds which are shorter and more reactive (Wade, 2013). High levels of oxidation deteriorate the oil quality and low levels improve the flavor of the food (Perkins, 1992). It is important to monitor the oil quality especially for oils with high levels of unsaturated fatty acids such as marine oils. The oxidation rate is usually predicted by testing for the peroxide value (PV). PV determines the concentration of hydroperoxide and is expressed in units of milliequivalents (meq) peroxide per 1 kg of oil (Kong, Singh, 2011). The lower the PV, the better the quality of oil. The values of PV for fresh oil vary from market to market; and for Frito-Lay, a PV of 1 meq/kg is considered fresh.

Fatty Acid Composition of Canola and Corn Oil		
Canola Oil	**Unsaturated Fatty Acids (92%)**	**Saturated Fatty Acids (6%)**
	Oleic (56%)	Palmatic (4%)
	Linoleic (26%)	Stearic (2%)
	Linolenic (10%)	
Corn Oil	**Unsaturated Fatty Acids (84%)**	**Saturated Fatty Acids (16%)**
	Linoleic (52%)	Palmatic (13%)
	Oleic (31%)	Stearic (3%)
	Linolenic (1%)	

Table 1: Unsaturated and Saturated Fatty Acid Composition of Canola and Corn Oil. (Guntone, 1996)

Polymerization:

Polymerization of oil leads to the formation of cyclic compounds. During frying, free radicals tend to react with each other or with fatty acids to form cyclic compounds. The compounds formed can be classified in two categories, non-polar dimers and polymers, and polar dimers and polymers. The formation of dimers and polymers increases with increasing temperature, the length of time the oil has been used for frying, and the presence of linoleic acid in the oils (Choe and Min, 2007). A high level of polymerization is usually not desired because it causes the oil to be sticky (Choe and Min, 2007)

Chip Fryer Mass Balance

A mass balance accounts for all the material present in a physical system. It is based on the law of conservation of mass and is used to track the components present in a system. The chip frying process involves the inlet oil, inlet potato slices, outlet potato chips and oil evaporated during frying. The general equation for mass balance is as follow:

Input	+	***generation***	–	***output***	–	***consumption***	=	***accumulation***
(enters through system boundaries)		(produced within system boundaries)		(leaves through system boundaries)		(consumed within system)		(buildup within system)

Figure 3: General Mass Balance equation

It is assumed that the chip fryer is at steady state, which means that all of the oil entering is used completely. There is also no generation or consumption in the system. Therefore, the mass balance equation reduces to input equals to output. A component mass balance can then be performed on oil where the inlet oil equals to the oil absorbed by the potato chips and the oil evaporated. Figure 4 below shows a sample mass balance calculation on oil in the chip fryer for both canola and corn oil. The chip fryer mass balance is:

Oil introduced into fryer = oil absorbed into chips + oil evaporated

Figure 4: Chip Fryer Mass Balance

Absorption

Different oils have different rates of oil intake based on their physical and chemical properties (Vitrac, 2000). The rate of oil flow into the potato during frying is dictated by the mass transfer phenomena of diffusivity. A higher diffusivity into the potato means the oil enters the potato at a faster rate and would result in a higher oil content (Welty et al., 2008). The diffusivity of oil into the potato is dictated by the physical properties of the oil. (Cummins et. al, 2017).

Evaporation

The Killingly manufacturing plant has noticed condensed oil drops on the walls of the steam stack indicating that some oil leaves the fryer through evaporation. The smoke points of corn and canola oil are both above the temperature of the fryer, therefore there is a different mechanism for evaporation occurring. Nonetheless, the physical and chemical differences between the oils, will cause the evaporation rates to be different.

Stakeholders

Frito-Lay is one of the biggest consumers of frying oil in the United States. Therefore, even though canola oil is thought to be less efficient, the company must still buy it to maintain the market balanced. Our goal is that from our project Frito-Lay will understand why canola is less efficient. As a result from this project, Frito-Lay may have a greater understanding of the physical and chemical properties of canola and corn oil and their behavior during frying.

Methodology

The chip frying process can be investigated through a mass balance on oil and potato. As mentioned earlier, the process is assumed to be at steady state and therefore the mass balance for the chip frying process reduces to input equals output. The input is the oil that is fed into the chip fryer at a constant flow rate. The purpose of the experiments and methods presented in this section is to evaluate the loss of oil through evaporation and absorption. The experiments and methods in this section were designed to measure the amount of oil absorbed by the fried potato chips and the oil evaporated for both canola and corn oil.

Absorption

As mentioned in the background, absorption into the potato chips is one of the mechanisms through which oil gets consumed in the frying process. During frying, oil displaces a majority of the water in a potato slice as it is simultaneously absorbed. Frito-Lay indicated that they expect 35% oil by weight in their chips, regardless of the type of oil. The various properties of the oils such as viscosity and density can affect oil-uptake during frying which can result in different efficiencies. The purpose of the experiments was to quantify the amount of canola and corn oil absorbed by the potato chips.

Pilot Plant Experiments

As described in the background, Frito-Lay first removes excess moisture from the potato slices and fries them at 360°F for 3 minutes. A pilot plant was designed to replicate the chip frying process at Frito-Lay. The potato was peeled and sliced to the company's thickness specifications using a manual slicer. The potato slices were cut into squares to preserve consistency in size and shape. They were then patted dry and placed in the fryer. Frito-Lay uses a temperature control to maintain the temperature of the chip fryer at 360°F at all times. The temperature control adjusts the energy input into the fryer based on the temperature. An electric fryer without temperature control was used as it was the only available equipment that reached 360 °F. In order to properly simulate Frito-Lay’s process, the frying time had to be adjusted to account for the specific heat of each oil and for the efficiency of the electric fryer. During experimentation, it was found that the temperature of oil lowers when the potato slices come in contact with the oil. A standard time of frying was determined for each oil by measuring the amount time it would take to fry a potato chip to 35% oil by weight. This was done by testing various frying times and evaluating the amount of oil in the chip. The standard time for canola and corn oil were determined to be 10 and 8 minutes respectively. The detailed steps of this procedure can be observed in Appendix B4.

The oil was heated in an aluminum cup placed on the fryer for the amount of time mentioned above for each oil to reach 360F. This was done because when the oil was simply placed in the fryer, the slices moved around during frying, and sticking to each other and the walls of the fryer. This inhibited uniform frying. The aluminum cups were covered with other, empty aluminum cups to prevent heat loss. Using aluminum cups also allowed us to test canola and corn oil frying simultaneously which meant we could use the same potato head for both oils.

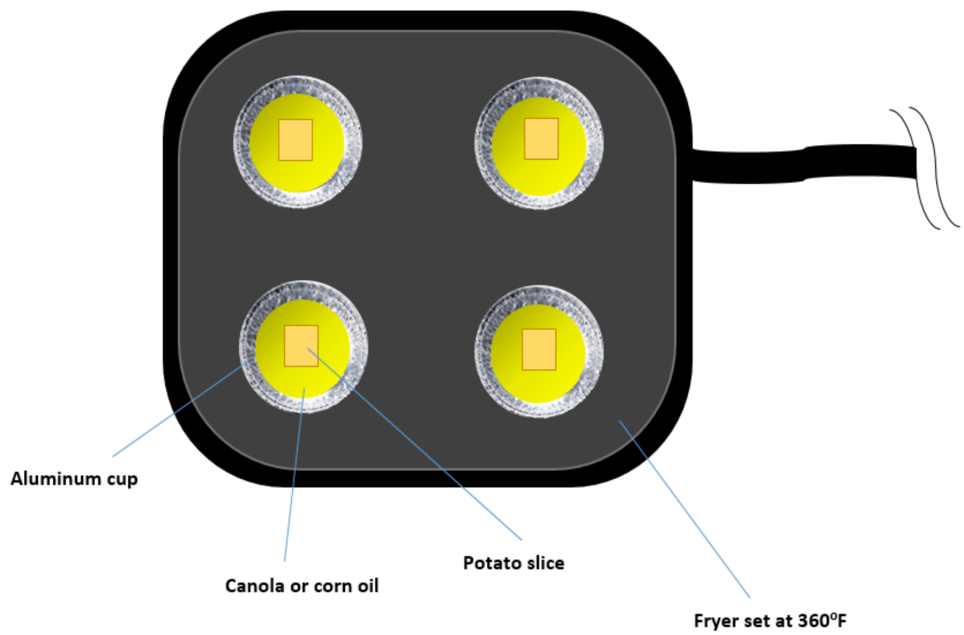


Figure 5: Schematic of the absorption experiment set-up

The chips were fried at 360 °F for the standard time that was determined for each oil. The temperature was monitored using a probe thermometer. After frying, the chips were removed, allowed to cool for 20 minutes, weighed and placed in hexane for extraction. Hexane is an alkane that is often used as solvent because of its ability to dissolve fats and oils. The chips were kept in hexane for 24 hours to extract all the oil. It has been found that only six hours are necessary to extract the all of the oil from the potato chip (Neff et al., 2002). After this, they were removed, allowed to dry for 30 minutes and weighed. The difference in the mass of the chip before and after extraction is considered to be the absorbed oil by the slices. To ensure accuracy, 27 trials were performed with each oil. Additionally, the same potato head was used for corresponding chips that were fried in different oils and compared. The step-by-step procedure of this experiment can be seen in Appendix B1.

Plant Scale Experiments

Unseasoned chips produced in Frito-Lay were also analyzed to confirm our results and establish consistency. In order to do this experiment, unseasoned potato chips fried at Killingly were collected. The chips were weighed and placed in hexane for 24 hours. The same process was used to examine the amount of oil absorbed. A total of 54 trials of each oil were performed. The step-by-step procedure of this experiment can be seen in Appendix B2.

Frito Lay's Quality Control Laboratory Data

The quality control lab at Frito-Lay is responsible for monitoring the oil content of the chips twice during each shift. The absorbance value obtained in the quality control lab is used to calibrate the infrared readers in the production line. The data were analyzed to observe if similar trends to the experimental data can be seen for each oil. Since Frito-Lay rarely run the plant using pure canola oil, only 15 days were available to collect data. Pure corn oil is used more often and data were collected from 85 days. Data were collected for selected dates between March 2017 and January 2018 when the plant was running pure canola and pure corn oil.

Evaporation

Evaporation is one of the mechanisms by which oil can leave the chip fryer. If there is a difference in the rate of evaporation for canola and corn oil, different amounts of each oil would be lost during frying. To quantify the loss of oil through evaporation, we conducted experiments to measure the amount of oil that evaporated during frying for both canola and corn oil. The skillet used during frying was fully sealed and a small hole was left where a tube was connected. The other side of the tube was attached to a flask immersed in an ice bath in order to condense and collect any gas that was formed in the skillet.

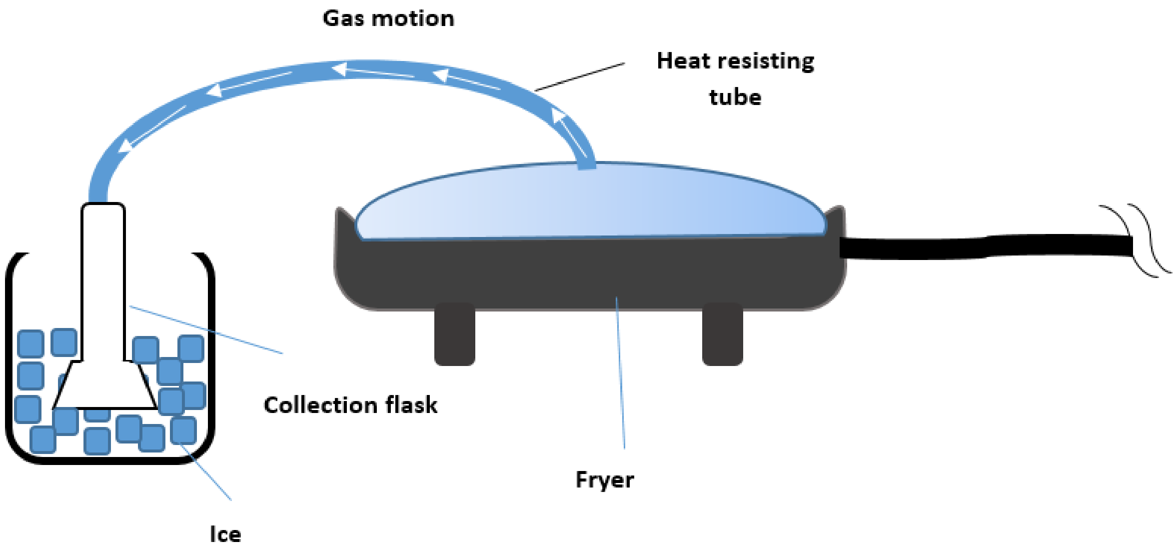


Figure 6: Evaporation Experiment Set-up

` This method proved to be ineffective as trials could not be accurately reproduced with the equipment available. Due to this, we did not continue with these experiments. Instead, a literature research of the different properties of oil that affect evaporation, as well as other gas-phase losses, was conducted to determine which oil evaporates at a higher rate. In addition, we conducted research to identify different methods to quantify the gaseous oil composition and particles in suspension found in the steam blanket above the fryer. We did this according to Frito-Lay’s accuracy needs and budget constraints for this specific problem.

Analysis of the Frito-Lay Process

In order to develop experiments that are reflective of the process at Frito-Lay, the process was studied extensively. Site visits were conducted to gain a practical understanding of the process. The site visits were beneficial in allowing us to see how the potato slices are prepared before frying and the visual appearance of the final product. During site visits we also met with operators who were able to explain how the equipment works and is controlled. The Quality Control technicians explained how they monitor the oil uptake in the potato chips, and perform tests on the oxidation, free fatty acid content, and polymerization of the oil.

A key factor studied was the equation used by Frito-Lay to calculate the oil efficiency. At the end of each shift the plant manager on shift calculates the oil efficiency using an equation established by the headquarters of the company. For efficiency purposes, Frito-Lay recognizes canola and corn oil as the same, and does not account for their different properties. Due to this, the values used to calculate the efficiencies of both oils are the same, without consideration that there may be differences in absorption or uptake. Our purpose in studying the efficiency equation was to quantify how absorption and evaporation affect the oil efficiency. The average absorption of canola and corn oil determined from the absorption experiments was used to estimate the amount of oil used for any given number of pounds of finished product. This amount of oil was inserted into the efficiency equation to calculate the efficiency of each oil for a given amount of pounds of finished product.

Density

The density of the two oils was determined to provide Frito-Lay more accurate information regarding their oil readings. Frito-Lay currently measures all of the oil they use in volume, but they conduct all their efficiency calculations using mass. They use the same factor when converting from volume to mass for both oils. The density of canola and corn oil was calculated to provide a more accurate value to use when converting between gallons of oil used to grams. The oil used for these experiments was provided by Frito-Lay. The density was determined by weighing 15 mL of each oil. The weight was divided by the volume to obtain a density measurement. All measurements were recorded and the same procedure was repeated 10 times for each oil. The detailed steps for this method are available in Appendix B3.

Results and Discussion

This section discusses the results obtained from the pilot and plant experiments as well as the quality control data collected. The reasons for differences in absorption are also explained. The literature research conducted to understand the evaporation of both oils is also presented in this section. Finally, the results are incorporated into Frito-Lays' efficiency equation to see if they account for the efficiency difference between the two oils.

Absorption

Pilot Scale Experiments

The oil uptake of potatoes was studied to examine its impact on the oil efficiency. In total, data were collected on 27 chips for each oil. Chips fried in canola oil absorbed 37.4%, while chips fried in corn oil absorbed 32.0% on average. As it can be seen in Figure 7 below, the range of absorption for canola oil was between 30.2% and 43.9%. The range for corn oil was between 25.0% and 41.0%. Note that the "chip number" axis in Figure 7 represents the order in which the chips were fried. The variance in oil absorption between each potato may be attributed to many factors such as the moisture content of the potato and the way in which the potato is sliced. The moisture content of each potato slice is inversely proportional to the oil absorption of the potato (Troncoso & Pedreschi, 2007). The way in which each potato slice was cut will also have an effect on oil absorption (Troncoso & Pedreschi, 2007).

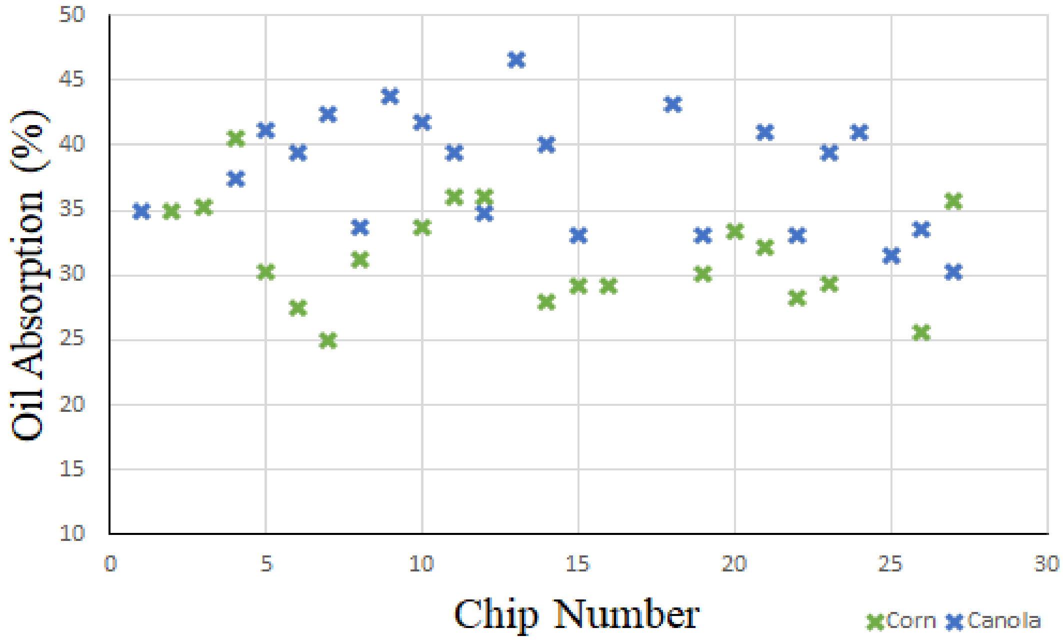


Figure 7: Oil absorption data from the pilot scale experiments.

Figure 8 below shows the average absorption observed for each potato head. As it can be seen for potato head 1, 3, and 4, the average absorption of canola oil is consistently higher by around 4%. Potato head 2 resulted in a larger difference of 6.9%. Since the average absorption of canola oil is higher in each potato head, it suggests that the properties of the oil cause it to have a higher absorption. The difference between the absorbance can be because of the use different potato chips for separate experiments.

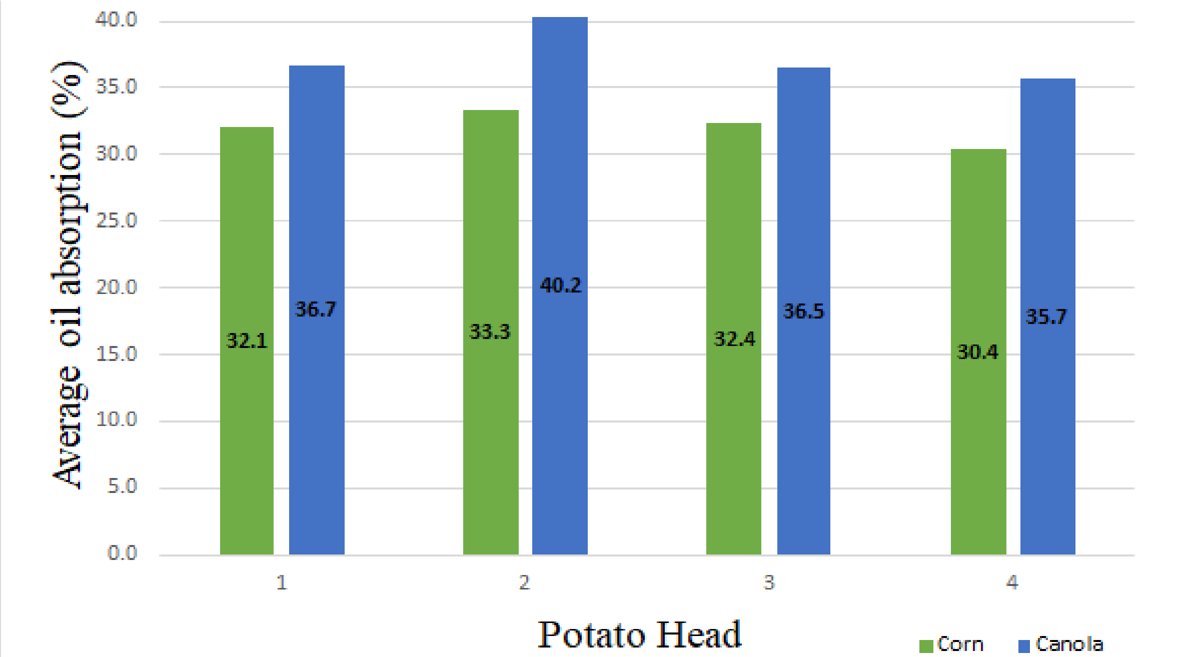


Figure 8: Average oil absorption of each potato head tested.
Each potato head consists of approximately 7 potato slices.

Plant Scale Experiments

Potato chips fried in canola and corn oil at the Killingly plant were also analyzed. The same oil extraction procedure as the pilot scale experiments was performed and data were collected on 54 chips for each oil. On average, chips fried in canola absorbed 32.3%, while chips fried in corn absorbed 29.1%. The range of absorption for canola oil was between 26.2% and 43.1%, while that of corn oil was 22.7% and 39.7%. The same discussion as with the pilot scale experiments regarding the moisture content of the potato slices and the cutting of the potato applies to the plant scale experiments. The fact that the absorption of canola oil was higher serves as a confirmation of the results from the pilot plant experiments. Figure 9 shows a graph of the data collected from the plant scale experiment. Note that each data point on the graph represents an average of three chips.

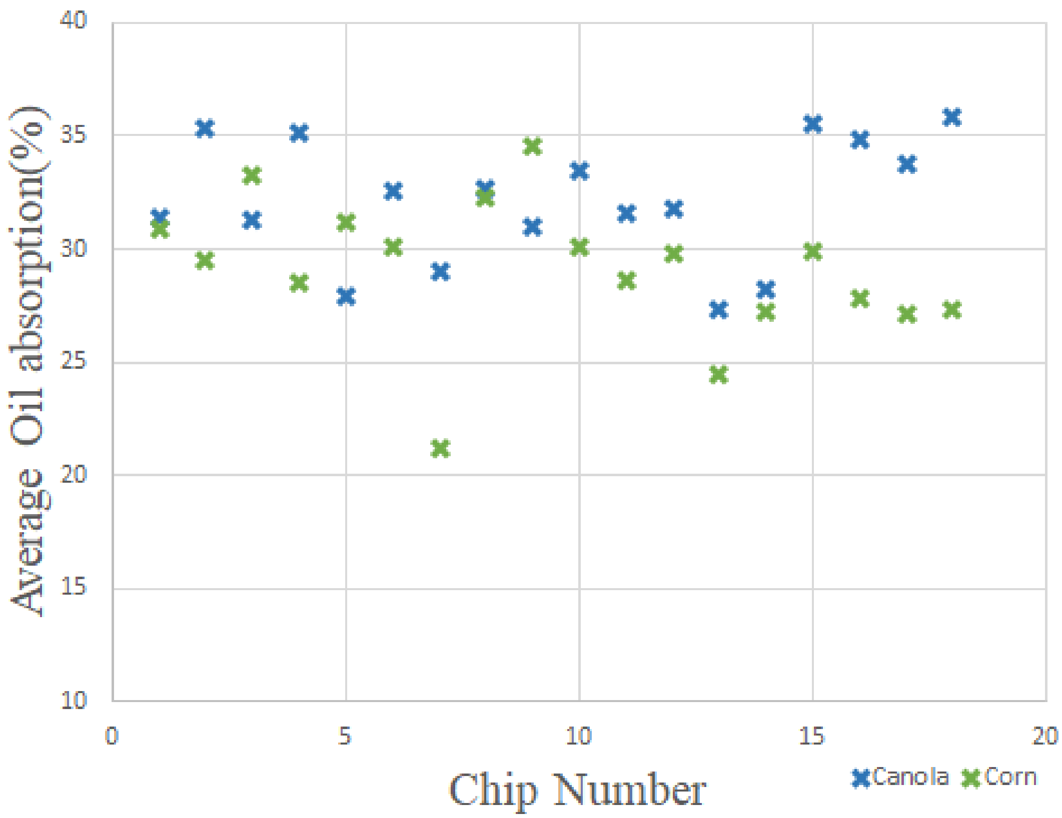


Figure 9: Average oil absorption measured for the plant scale experiments.

Quality Control Lab Data

Historical data from the Quality Control Lab at the Killingly plant were collected and analyzed as well. On average, the oil uptake of the potato chips fried in canola and corn oil was 36.6% and 32.8%, respectively. The range of absorption for canola oil was between 33.5% and 38.02, while that of corn oil was 28.34% and 42.53%. These data further reaffirmed the experimental data obtained through the pilot and plant scale experiments as canola was absorbed more than corn oil. As it can be seen in Figure 10 below, there was also a variance in oil absorption in the potato chips fried and analyzed at the Frito-Lay plant in Killingly which shows that the range we obtained experimentally is acceptable.

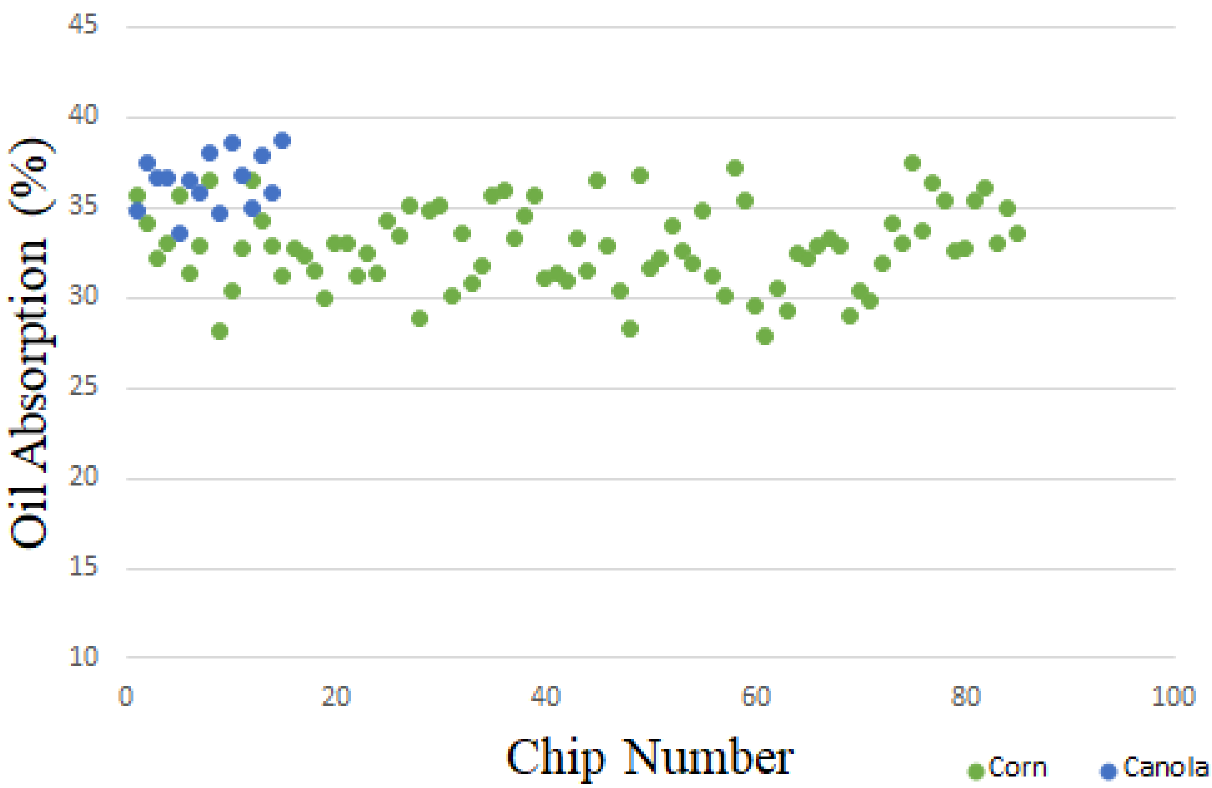


Figure 10: Oil absorption data collected from Frito-Lays quality control lab

Why is Canola Oil Absorbed More?

When the potato chip is immersed in hot oil, the heat of the oil causes the water inside the potato to evaporate and create voids (Dana and Saguy, 2006). Essentially, as a potato chip is entered into frying oil, a concentration gradient is created between the potato chip and the oil. Initially, the concentration of oil in the potato is zero which creates a driving potential for transport of oil into the potato chip. The Lucas-Washburn diffusion equation, shown in Equation 1 below, was used to explain diffusion of oil into the potato during frying. The Lucas-Washburn Equation was chosen because it applies to diffusion of liquid through porous membranes.

$$L^2 = \frac{4C\gamma\ \cos(\theta) r}{\mu\varphi} t$$

Equation 1: Lucas-Washburn Equation

L = length of diffusion
γ = surface tension of the oil
θ = contact angle
r = radius of the pores
μ = viscosity of the oil
t = time

The properties specific to the type of oil involved in this equation are the viscosity and the surface tension. The other factors that are considered in the Lucas-Washburn equation are related to the potato itself, and therefore will be assumed to be constant.

Given the viscosity and the surface tension of canola and corn oil, the Lucas-Washburn equation was used to develop a theoretical prediction for the absorption of each oil. The viscosity of canola and corn oil at 180 °C is 4.65 mPa s and 3.33 mPa s, respectively (Fasina and Colley, 2008). There is limited research regarding the surface tension of vegetable oils. Melo-Espinosa et al. performed a compiled surface tension readings for various vegetable oils (2014). They reported the surface tension of corn oil to be in the range of 33.40 - 33.80 mN/m but the surface tension of canola oil was not reported. Instead, the surface tension of rapeseed oil, which belongs to the same family as canola oil, was reported to be in the range of 32.90 - 33.83 mN/m. Due to the lack of more precise data on the surface tension of both oils, the ranges reported by Melo-

Espinosa suggest that the surface tensions of both oils are close to equal. According to the Lucas-Washburn equation, since the viscosity of canola oil is higher, then the length “L,” or depth, that the canola oil will diffuse into the potato will be less. This means that the potato will absorb less canola oil during the frying step.

However, several studies have found that potato chips absorb most of the oil during the cooling step as opposed to the frying step (Dana and Saguy, 2006). A study conducted by Moreira et al. found that around 75% of the oil is absorbed during the cooling step, compared to 25% during the frying step (1997). Based on this, our study will consider the cooling step as the primary mechanism for oil absorption in the potato chip.

When a potato chip is removed from the fryer and is allowed to cool, the heat loss causes the water vapor left inside the potato to condense. The condensation of the water vapor causes a decrease in the pressure inside the potato, which creates a “vacuum effect” that pushes the oil into the potato and leads to oil absorption (Moreira, 1997). During the cooling step, viscous oils have been found to be absorbed at a higher rate. This is because the “viscosity of the oil is directly correlated to the coating kinetics and adsorbing amounts” (Yaghmur et al. 2001). Essentially this means that when chips are removed from the frying oil, the more viscous oil has a higher tendency to stick to the chip surface. This surface oil then becomes available for absorption during the cooling step.

Our experimental results and Frito-Lay's absorption data all indicated that canola's absorption was 3% to 5% higher than corn's. Figure 11 below, shows the average absorption results from the experimental and quality control data. At 180 °C, the viscosities of canola oil and corn oil are 4.65 mPa s and 3.33 mPa s, respectively (Fasina and Colley, 2008). This difference in the viscosity of the two oils contributes to the difference in absorption.

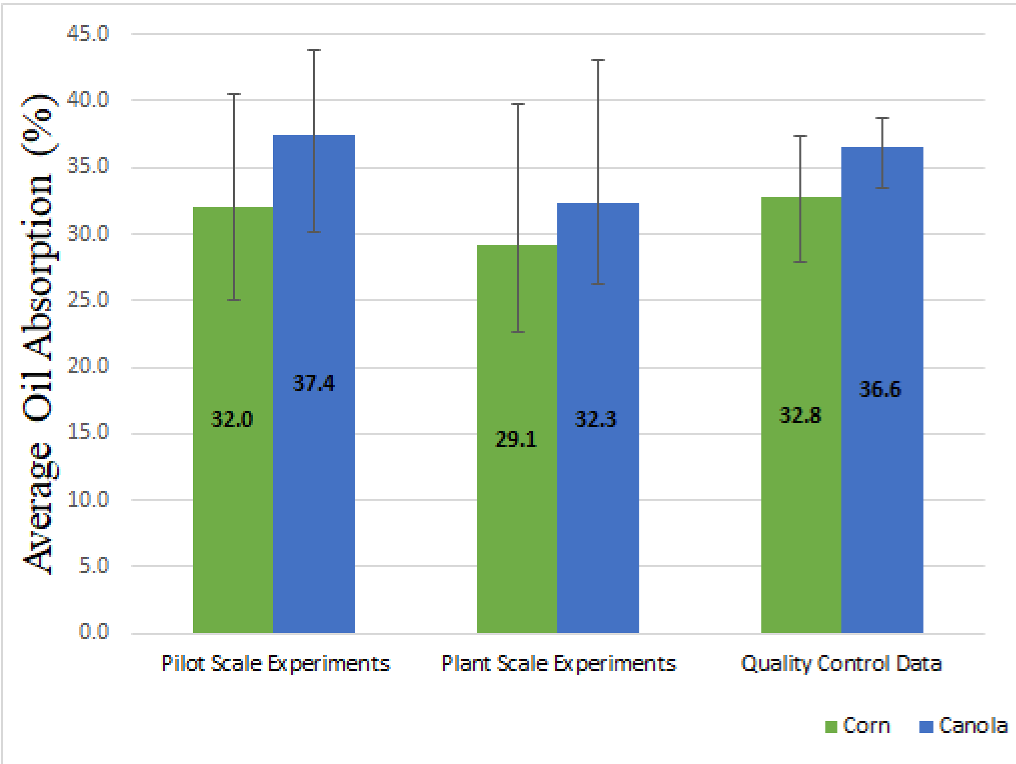


Figure 11: Average oil absorption of pilot scale experiments, plant scare experiments, and quality control data.

Evaporation

Evaporation is one of the main outflows of oil from the chip fryer. Process operators at Frito-Lay have observed oil residue on the outside of the fryers, which could be an indicator that oil is lost through the steam stack above the fryer (Eber, personal communication). However, as mentioned in the background, the frying temperature is 360 ^{o}F which is below the boiling point of the triglycerides that make up the oils and below the smoke points of the both oils.

A significant contributor to the volatile compounds formed during the frying process is due to the chemical reactions that oil undergoes during frying. The main reactions occurring during frying are oxidation due to presence of air in the fryer and hydrolysis due to heat and presence of water from potato slices (Nawar, 1996). As mentioned earlier, the rates of hydrolysis and oxidation depend on the fatty acid content of the oil. An oil that is higher in unsaturated fatty acids will oxidize faster. Canola oil is composed of 92% unsaturated fatty, while corn oil is composed of 84% unsaturated fatty acids (Gunstone, 1996).

The mechanism of oxidation favors canola oil since it has a higher amount of unsaturated fatty acids. Similarly, hydrolysis is favored in canola oil as it is more soluble in water. Glycerol, one of hydrolysis' product evaporates at 150^{o}C and so leaves the system and enters the steam stack. Even though volatiles are very important to the flavor of fried foods, the concentration of these volatiles produced is in the parts per million (Nawar, 1985). This amount would make it very difficult to detect a difference between volatile production in canola and corn oil.

Aerosolization

Aerosolization is the process by which small liquid particles are elevated into air due to bursting bubbles. During frying, aerosolization of oil droplets is caused by the water vapor generated from the potatoes. As the water bubbles burst, small particles of oil are aerosolized and suspended in the steam blanket. Since the oil does not have to be boiling for aerosolization to occur, it is a more plausible explanation for the loss of oil observed through the steam stack. Whether or not there is a significant amount of oil in the steam blanket and whether there is a large discrepancy between the aerosolization rate of canola and corn oil is beyond the scope of this project. Still, an investigation on the parameters affecting aerosolization in oil was conducted in order to gain an understanding on this process and its effect on oil efficiency of both oil.

While investigating the presence of water in the air above the sea, Lhussier and Villermaux discovered that in situations where liquids produce many bubbles, such as waves crashing onto each other, the rate of aerosolization greatly surpasses the effect of evaporation (2011). The main properties affecting the aerosolization of oil, according to different journals, are surface tension and viscosity of the bubbling liquid. This is because these two properties dictate the physics and formation of bubbles. While viscosity determines if a bubble forms on the surface of the liquid, surface tension controls the bubbles' ability to leave the fluid (Lhussier and Villermaux, 2011).

Viscosity reduces aerosolization by limiting the aerosol jet kinetic energy (Wang et al., 2009). This means that the oil particles that aerosolized either do not make it very high or fall back into the liquid, reducing the amount lost to the gas phase. Wang et al. also concluded that surface tension reduces rate of aerosolization (2010). For a liquid with a high surface tension, it will be more difficult for bubbles to burst and produce aerosols (Wang et al., 2010).

A study on the effect of surfactants on the quantity of aerosol formed showed that adding surfactants reduces the surface tension of a fluid by changing the relative strengths of the bonds in the fluid (Modini et. al, 2013). Modini et. al observed a 79-98% reduction in aerosol production after a surfactant was added to the liquid (Modini et. al, 2013). Yet, this contradicts the relation between aerosolization and surface tension that Wang et. al found in their study. Modini goes on to conclude that the effect of surface tension on bubble bursting is complex and probably depends on other factors like time dependent properties of bubbles and their thickness.

Aside from the effect of surface tension being too complex to model, as it was said earlier, reliable information regarding the surface tension of canola and corn oil is not available. Aerosolization is a function of both viscosity and surface tension, and without adequate information on the surface tension of the oils, it is not possible not know which oil will have a higher aerosolization rate. Although corn oil has a lower viscosity, the effect of surface tension may counteract its ability to form aerosols. In conclusion, the effect of evaporation on the oil efficiency cannot be determined due to lack of information on the effect of oil properties on aerosolization. Therefore, in regard to oil efficiency, we focused on the difference in absorption rates of canola and corn oil.

Efficiency Equation

We analyzed how the difference in canola and corn oil absorption affects oil efficiency using Frito-Lay's efficiency equation. The actual cost and bulk formula are two terms in the efficiency formula that are directly affected by absorption. The bulk formula represents the amount of oil that the plant expects to use to fry 1,000 lb of potato chips, while the actual cost is the cost of the exact amount of oil that was used. The bulk formula for canola and corn oil for the Killingly plant is 293.11 lb at 91.2% plan efficiency. This number does not reflect the difference in absorption, as it currently reflects that they expect to use the same amount of canola and corn oil. With a 3%-5% difference in absorption, 32,000 lb of corn oil are needed to produce 100,000lb of potato chips compared to 37,000 lb of canola oil. This leads to the actual cost of corn and canola to be around $16,000 and $18,000, respectively. Overall, accounting for absorption, canola is 9% to 14% less efficient than corn oil.

Density

The density of the oils was determined to provide Frito-Lay more accurate information for the conversion of their oil readings. Experimentally, we found the densities of canola and corn to be 7.60 lb/gallon and 7.65 lb/gallon respectively. The density of canola and corn oil has been reported to be 7.57 lb/ gallon and 7.67 lb/gallon (Noureddini et al., 1992).

Conclusion

The efficiency difference between canola and corn oil was determined to be due to absorption. Our experiments and the Frito-Lay quality control data showed that canola oil is absorbed 3% to 5% more than corn oil on average. Canola oil is absorbed because it has a higher viscosity, which causes it to stick to the surface of the chip more and then diffuse more into the chip. According to the Frito-Lay efficiency equation, canola oil is 9% to 14% less efficient than corn oil. The results of our project will help Frito-Lay understand why canola oil is less efficient which will allow them to make informed decisions in the future.

Recommendations

Bulk Formula

The bulk formula used at Frito-Lay is the amount of oil expected to be used to fry 1,000 pounds of finished product. Frito-Lay uses the same bulk formula for canola and corn oil which means that they estimate to use the same amount of canola and corn oil to produce the potato chips. However, the results from the experiments conducted and the data collected from Frito-Lay's quality control lab show that the potato chips absorb 3% to 5% more canola than corn oil. Based on this, we recommend that the bulk formula of canola oil should be increased by 3 to 5% to account for the higher absorption.

Composition of Oil in the Steam Stack

The Frito-Lay plant in Killingly expressed interested in finding equipment that can measure the gaseous composition of the steam present inside the fryer. This will help them know the amounts of gaseous oil formed during frying, as well as an accurate identification of the components in the steam stack.

The first method we recommend uses a flame ionization analyzer (FIA) to collect high accuracy data on the identity and concentration of the hydrocarbons present in the gas. A gaseous sample is taken from the source through a probe placed in the stack. The sample is then heated to 220 ^{o}F throughout the sampling period using a piping system that creates a flame, as seen in Figure 12 below. It is then sent to an organic analyzer. Propane is usually used as the calibration gas, but other gases can also be used. The data collected is recorded as the average organic concentration in terms of ppmv of a known concentration of the calibration gas used. The data of composition of oil in the steam stack can be collected in a computer at a rate of 1 measurement per minute. This method has extremely high accuracy but is limited by its high cost. This equipment would be important to have if there is need for constant information on the composition and quantity of oil in the stack (Cornell University, 1971).

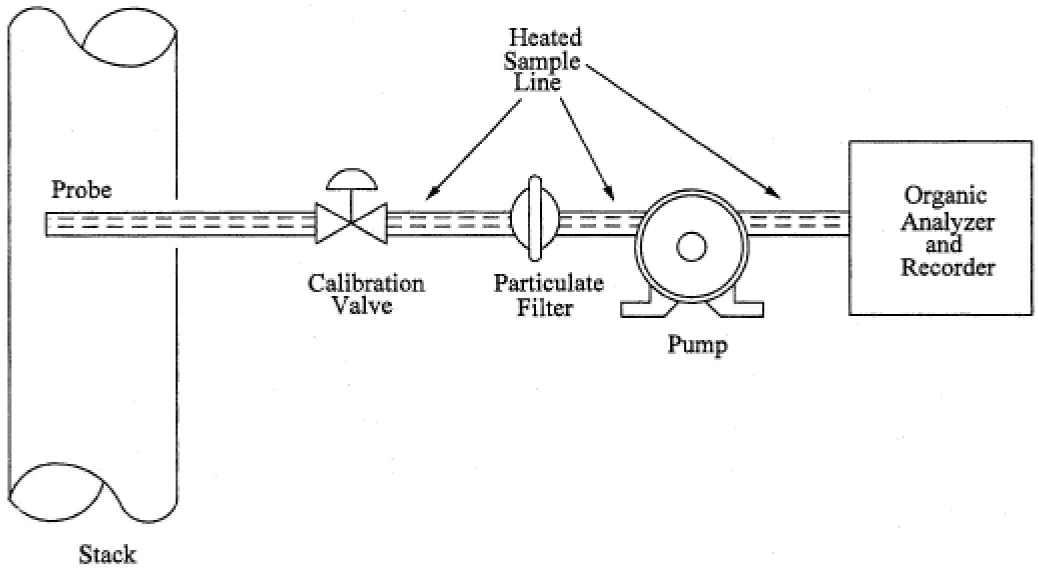


Figure 12: The flame ionization method

The second method is manual and uses a gas sampling pump. It requires an operator to physically place the tip of the detector tube into the gas and take a sample. Although this method does not give the identity of the gas particles, it does give accurate data on the concentration when calibrated to the main gas (in this case steam). There exists numerous detector tubes for different gases. For oil samples, the polytec detector tubes shown in Figure 13 below are commonly used. Unlike the FIA method, you cannot obtain real-time data of the concentration of gas, instead there is a total sampling and detection time of 20 minutes. When the sampling time has elapsed, the light on top of the gas pump will turn white and readings can be recorded. This method is easy to use and can be used to compare concentrations of gaseous oils in the steam stack for canola and corn oil. This information can then be used to factor in the effect of evaporation in the oil efficiency. Although this equipment's concentration readings are less accurate, this method is useful when comparing the relative concentrations of different samples (Gastec, 2017).

Figure 13: Pump-detector tube apparatus made by Gastec Corporation.

Specific Heat

We observed during the pilot scale experiments that it took a longer time to heat canola oil to 360 °F, due to the difference in specific heat of the two oils. The specific heat of canola oil is 2.64 KJ/Kg K and 2.05 KJ/Kg K for corn oil. Different specific heats would lead to different amounts of energy required to heat the oil. In addition to evaluating the amount of oil used during frying, Frito-Lay should also consider their energy consumption to evaluate if there is an additional expense for maintaining canola oil at 360°F.

Density

Frito-Lay obtains their oil readings from the silos in gallons, however the efficiency calculations are performed in pounds. In order to convert from gallons to pounds, they use the same density, of 7.6 Ib/gallon for both canola and corn oil. The density of canola and corn oil were found to be different experimentally and in literature. Experimentally we found the densities of canola and corn to be 7.60 lb/gallon and 7.65 lb/gallon respectively.

Bibliography

2016 PepsiCo Annual Report. (2017, February 15). Retrieved November 11, 2017, from http://www.pepsico.com/docs/album/annual-reports/pepsico-inc-2016-annual-report.pd

Choe, E. and Min, D.B. (2007), Chemistry of Deep-Fat Frying Oils. Journal of Food Science, 72: R77–R86. doi:10.1111/j.1750-3841.2007.00352.x

Cornell University, Code of Federal Regulations - Protection of Environment. Chapter 40. (1971). Retrieved from https://www.law.cornell.edu/cfr/text/40

Dana, Dina, and Sam Saguy (2006). Review: Mechanism of oil uptake during deep-fat frying and the surfactant effect-theory and myth. Advances in Colloid and Interface Science, *ScienceDirect*, doi.org/10.1016/j.cis.2006.11.013.

Fasina, O., & Colley, Z. (2008). Viscosity and Specific Heat of Vegetable Oils as a Function of Temperature: 35°C to 180°C. *International Journal of Food Properties,11*(4), 738-746. doi:10.1080/10942910701586273

Forbes Trefis Team. “Frito-Lay Dominates U.S. Salty Snacks, But Rising Cracker Sales Could Stall Growth.” *Forbes*, June 2014,

Gastec Corporation. (2017). Types of detector tube. Retrieved January 31, 2018, from https://www.gastec.co.jp/en/product/detector_tube/type/

Gunstone, FD. Fatty Acid and Lipid Chemistry. London: Blackie Academic & Professional, 1996. Print.

Houhoula DP, Oreopoulou V, Tzia C. 2003. The effect of process time and temperature on the accumulation of polar compounds in cottonseed oil during deep-fat frying. *J Sci Food Agric* 83:314–9.

Melo-Espinosa, Eliezer Ahmed, et al. “Surface Tension Prediction of Vegetable Oils Using Artificial Neural Networks and Multiple Linear Regression.” 2013, doi:doi: 10.1016/j.egypro.2014.10.298.

Miller, Matt. “Oxidation of Food Grade Oils.”

Moreira, Rosana G., et al. “Factors Affecting Oil Uptake in Tortilla Chips in Deep-Fat Frying.” *Journal of Food Engineering*, Elsevier, 9 Dec. 1997, www.sciencedirect.com/science/article/pii/S026087749600088X.

Noureddini, Hossein; Teoh, B C.; and Clements, L Davis, "Densities of Vegetable Oils and Fatty Acids" (1992). Papers in Biomaterials. 14.

Perkins, Edward. “Effect of Lipid Oxidation in Oil and Food Quality during Frying.” Effect of Lipid Oxidation in Oil and Food Quality during Frying, 5 Aug. 1992.

“Potato Chips Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2017 - 2022.” *Research and Markets* , Research and Markets, Feb. 2017, www.researchandmarkets.com/research/gcf258/potato_chips.

Przybylski, Roman. *Canola Oil: Physical and Chemical Properties*. Canola Council, canolacouncil.org/media/515239/canola_oil_physical_chemical_properties_1.pdf.

Santos , José, et al. *THERMAL STABILITY OF COMMERCIAL EDIBLE OILS BY THERMOGRAVIMETRY*.

Sharma, Rajan, and Bimlesh Mann. *Changes Occurring in Oils and Fats during Frying*.

Troncoso, E., & Pedreschi, F. (2009). Modeling water loss and oil uptake during vacuum frying of pre-treated potato slices. *LWT - Food Science and Technology,42*(6), 1164-1173. doi:10.1016/j.lwt.2009.01.008

Wade, L. G. (2013). *Organic chemistry* (8th ed.). Boston: Pearson.

Welty, James R., et al. *Fundamentals of Momentum, Heat, and Mass Transfer*. 5th ed., Wiley, 2008.

Neff W.E. Eller. F & Warner. K (2002) Composition of oils extracted from potato chips by supercritical fluid extraction. U.S.: Consumption of Potato Chips 2011-2020. *Statista*. N.p., 2018.

Ziaiifar, A. M., Achir, N., Courtois, F., Trezzani, I., & Trystram, G. (2008). Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process. *International Journal of Food Science & Technology,43*(8), 1410-1423. doi:10.1111/j.1365-2621.2007.01664.x

Appendices

Appendix A: Properties of Canola and Corn Oil

Property	Canola Oil	Corn Oil
Specific Heat	2.64 KJ/Kg K [1]	2.05 KJ/Kg K [1]
Smoke Point	400^{o}F	450^{o}F
Viscosity	4.65 mPa s [1]	3.33 mPa s [1]

Table I: Properties of Canola and Corn Oil
(Fasina and Colley, 2008 [1])

Specific Heat: The specific heat is a physical property of a substance that describes the energy required to raise the temperature of 1g of a substance by 1^{o}C.

Smoke point: The smoke point of an oil is the temperature at which the oil starts to produce smoke under defined conditions. It can be affected by level of refinement/filtration, fatty acid composition, field conditions, season and age of oil.

Viscosity: The viscosity is a measure of a fluid's resistance to flow.

Appendix B: Experiments Procedure

B1. Pilot Scale Experiments

1. Pour 15 mL of canola or corn in an aluminum cup.
2. Set skillet to 360^{o}F.
3. Put the aluminum cup in the skillet and measure T until it reaches 360^{o}F.
4. Cover the skillet.
5. While the skillet reaches 360 ^{o}F, cut the potatoes into slices.
6. Pat potatoes dry.
7. Put the potato in the oil and let it fry until brown and hard.
   a. Corn for 8 minutes.
   b. Canola for 10 minutes.
8. Turn skillet off when the frying is complete.
9. Remove potato slices from the oil and put them on weighing paper to dry excess oil for 15 minutes.
10. Weigh the potato chips once the frying time has passed.
11. Place each chip in a 20 mL beaker of hexane.
12. Cover the beaker and let it sit for 24 hours.
13. Remove the potatoes from hexane and place on a paper towel.
14. Let potatoes dry for 30 minutes.
15. Weigh the dry potatoes and record the mass.

B2. Plant Scale Experiments

1. Weigh the potato chips.
2. Place each chip in a 20 mL beaker of hexane.
3. Cover the beaker and let it sit for 24 hours.
4. Remove the potatoes from hexane and place on a paper towel.
5. Let potatoes dry for 30 minutes.
6. Weigh the dry potatoes and record the mass.

B3. Density

1. Tare the mass of a measuring cylinder in the digital balance.
2. Fill a beaker with approximately 25 mL of oil.
3. Transfer 25 mL of oil into the measuring cylinder.
4. Weigh the mass of the graduated cylinder and the oil and record it.

B4. Determination of a Standard Frying Time:

1. Place 15 mL of oil into an aluminum cup and place it on the fryer.
2. Set fryer to 360^{o}F.
3. Cut the potato into slices.
4. Place each potato slice in an aluminum cup with hot oil.
5. Prepare 5 aluminum cups with for each oil.
6. Let each potato slice fry for 7, 8, 9, 10, 11, and 12 minutes for both oils.
7. Remove the potato chips from the frying oil.
8. Weigh the potato chips.
9. Place each potato slice in a 20 mL beaker with hexane.
10. Let the beaker with hexane sit for 20 mL for 24 hours.
11. Remove the potato chips from the hexane and weigh them.
12. Record the absorption of each potato.
13. Note the amount of time it took for a potato chip to get an absorption of 35%.

Appendix C: Experimental Data

C1. Pilot scale experiments:

C1.1. Absorption % data collected for chips fried in corn oil:

Chip number	Trial		Absorption %
1	Trial 1	Chip 1	31.0
2		Chip 2	35.0
3		Chip 3	35.3
4		Chip 4	40.5
5		Chip 5	30.3
6		Chip 6	27.5
7		Chip 7	25.0
8	Trial 2	Chip 1	31.2
9		Chip 2	40.6
10		Chip 3	33.7
11		Chip 4	36.0
12		Chip 5	36.0
13		Chip 6	27.8
14		Chip 7	28.0
15	Trial 3	Chip 1	29.2
16		Chip 2	29.2
17		Chip 3	33.4
18		Chip 4	39.3
19		Chip 5	30.2
20		Chip 6	33.4
21		Chip 7	32.1
22	Trial 4	Chip 1	28.2
23		Chip 2	29.4
24		Chip 3	31.0
25		Chip 4	29.4
26		Chip 5	25.5
27		Chip 6	35.7

C1.2. Absorption % data collected for chips fried in canola oil:

Chip number	Trial		Absorption %
1	Trial 1	Chip 1	35.0
2		Chip 2	36.8
3		Chip 3	33.4
4		Chip 4	37.4
5		Chip 5	41.1
6		Chip 6	39.4
7	Trial 2	Chip 1	42.4
8		Chip 2	33.7
9		Chip 3	43.9
10		Chip 4	41.8
11		Chip 5	39.4
12		Chip 6	34.7
13		Chip 7	46.6
14	Trial 3	Chip 1	40.1
15		Chip 2	33.1
16		Chip 3	40.1
17		Chip 4	33.1
18		Chip 5	43.2
19		Chip 6	33.1
20		Chip 7	33.0
21	Trial 4	Chip 1	41.0
22		Chip 2	33.1
23		Chip 3	39.4
24		Chip 4	41.0
25		Chip 5	31.5
26		Chip 6	33.6
27		Chip 7	30.2

C2. Plant scale experiments:

Day 1					
Bag 1 (4am)	Before	After	Mass of Oil	Oil %	**Average**
Chip 1	1.8207	1.135	0.6857	37.66133905	
Chip 2	0.8738	0.6275	0.2463	28.1872282	
Chip 3	1.17	0.839	0.331	28.29059829	
					31.37972184
Bag 2 (4 am)					
Chip 1	1.2211	0.7221	0.499	40.86479404	
Chip 2	1.8684	1.2344	0.634	33.93277671	
Chip 3	0.897	0.6163	0.2807	31.29319955	
					35.3635901
Bag 3 (6 am)					
Chip 1	0.8187	0.5527	0.266	32.49053377	
Chip 2	0.5675	0.3926	0.1749	30.81938326	
Chip 3	1.6271	1.1319	0.4952	30.4345154	
					31.24814414
Bag 4 (6 am)					
Chip 1	0.8641	0.5482	0.3159	36.55826872	
Chip 2	1.6254	1.0988	0.5266	32.39817891	
Chip 3	0.601	0.3823	0.2187	36.38935108	
					35.11526624
Bag 5					
Chip 1	1.8153	1.3363	0.479	26.38682311	
Chip 2	0.903	0.6648	0.2382	26.37873754	
Chip 3	2.2753	1.5716	0.7037	30.92778974	
					27.89778347
Bag 6					
Chip 1	1.4736	1.078	0.3956	26.84581976	
Chip 2	1.9318	1.1611	0.7707	39.89543431	
Chip 3	1.1013	0.7604	0.3409	30.9543267	
					32.56519359

C2.1 Absorption of chips fried in canola oil:

Day 2					
Bag 1 (4am)	Before	After	Oil	Oil %	
Chip 1	1.5313	1.0451	0.4862	31.75079997	
Chip 2	1.098	0.7904	0.3076	28.01457195	
Chip 3	1.3737	0.9986	0.3751	27.30581641	
					29.02372944
Bag 2 (4 am)					
Chip 1	1.49	1.0206	0.4694	31.5033557	
Chip 2	1.8694	1.2423	0.6271	33.54552263	
Chip 3	1.3893	0.9316	0.4577	32.94464838	
					32.66450891
Bag 3 (6 am)					
Chip 1	2.0545	1.3513	0.7032	34.22730591	
Chip 2	1.7625	1.2067	0.5558	31.53475177	
Chip 3	1.4384	1.047	0.3914	27.21078977	
					30.99094915
Bag 4 (6 am)					
Chip 1	1.3095	0.9059	0.4036	30.82092402	
Chip 2	0.9	0.5637	0.3363	37.36666667	
Chip 3	1.4463	0.981	0.4653	32.1717486	
					33.45311309
Bag 5					
Chip 1	1.3796	1.0071	0.3725	27.00057988	
Chip 2	1.0639	0.6751	0.3888	36.54478804	
Chip 3	1.373	0.9459	0.4271	31.10706482	
					31.55081091
Bag 6					
Chip 1	1.7112	1.1755	0.5357	31.3055166	
Chip 2	1.3928	0.8253	0.5675	40.74526134	
Chip 3	1.4944	1.1003	0.3941	26.37178801	
					31.74843892

Day 3						
Bag 1 (4am)	Before	After	Oil	Oil %		
Chip 1	0.914	0.6598	0.2542	27.81181619		
Chip 2	1.2016	0.8662	0.3354	27.91278296		
Chip 3	0.9934	0.7329	0.2605	26.22307228		
			0		27.31589048	
Bag 2 (4 am)			0			
Chip 1	1.2066	0.8442	0.3624	30.03480855		
Chip 2	0.8843			N/A		
Chip 3	1.3636	1.0026	0.361	26.47403931	28.25442393	
			0			
Bag 3 (6 am)			0			
Chip 1	1.727	1.0389	0.6881	39.84365953		
Chip 2	1.3248	0.8993	0.4255	32.11805556		
Chip 3	1.5591	1.018	0.5411	34.70592008		
			0		35.55587839	
Bag 4 (6 am)			0			
Chip 1	1.4413	0.9764	0.4649	32.25560258		
Chip 2	0.9165	0.5995	0.317	34.58810693		
Chip 3	1.4028	0.8752	0.5276	37.6104933		
			0		34.8180676	
Bag 5			0			
Chip 1	2.4905	1.524	0.9665	38.80746838		
Chip 2	1.2921	0.941	0.3511	27.17281944		
Chip 3	1.6848	1.09	0.5948	35.30389364		
			0		33.76139382	
Bag 6			0			
Chip 1	1.4809	0.965	0.5159	34.83692349		
Chip 2	1.6418	1.1543	0.4875	29.69301986		
Chip 3	1.1542	0.6573	0.4969	43.05146422	35.86046919	
					32.8496439	
					Overall average :	**32.27594236**

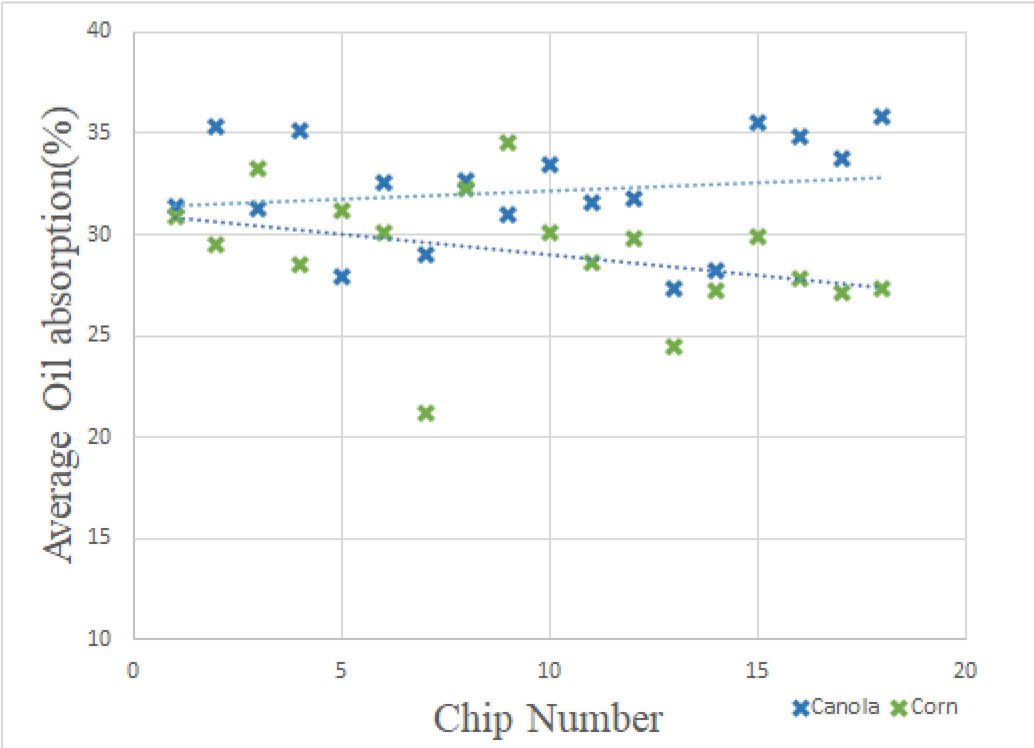
C2.2 Absorption of chips fried in corn oil:

Day 1					
Bag 1 (4am)	Before	After	Mass of Oil	Oil %	
Chip 1	0.7491	0.5522	0.1969	26.28487518	
Chip 2	1.3945	0.8689	0.5256	37.69092865	
Chip 3	0.8175	0.5827	0.2348	28.72171254	
					30.89917212
Bag 2 (4 am)					
Chip 1	1.1615	0.7653	0.3962	34.11106328	
Chip 2	1.462	1.1215	0.3405	23.29001368	
Chip 3	0.9154	0.6293	0.2861	31.25409657	
					29.55172451
Bag 3 (6 am)					
Chip 1	1.0713	0.6723	0.399	37.24446934	
Chip 2	0.9614	0.6455	0.3159	32.8583316	
Chip 3	0.946	0.6662	0.2798	29.57716702	
					33.22665599
Bag 4 (6 am)					
Chip 1	1.3588	1.0029	0.3559	26.19222844	
Chip 2	0.8434	0.5551	0.2883	34.18306853	
Chip 3	1.4679	1.0974	0.3705	25.24013897	
					28.53847865
Bag 5					
Chip 1	1.012	0.6905	0.3215	31.7687747	
Chip 2	1.5723	1.1534	0.4189	26.64249825	
Chip 3	1.054	0.6844	0.3696	35.06641366	
					31.15922887
Bag 6					
Chip 1	1.195	0.8343	0.3607	30.18410042	
Chip 2	0.8719	0.6585	0.2134	24.47528386	
Chip 3	1.0027	0.7392	0.2635	26.27904657	
					30.05912285

Day 2					
Bag 1 (4am)	Before	After	Oil	Oil %	
Chip 1	1.1109	0.824	0.2869	25.82590692	
Chip 2	0.796	0.5817	0.2143	26.92211055	
Chip 3	1.1105	0.9903	0.1202	10.82395317	
					21.19065688
Bag 2 (4 am)					
Chip 1	0.6785	0.5019	0.1766	26.02800295	
Chip 2	1.3981	0.9618	0.4363	31.20663758	
Chip 3	1.372	0.8274	0.5446	39.69387755	
					32.30950603
Bag 3 (6 am)					
Chip 1	0.7381	0.5011	0.237	32.10947026	
Chip 2	1.3479	0.824	0.5239	38.86786854	
Chip 3	1.7098	1.1491	0.5607	32.79330916	
					34.59021599
Bag 4 (6 am)					
Chip 1	0.8091	0.609	0.2001	24.7311828	
Chip 2	1.2902	0.8456	0.4446	34.45977368	
Chip 3	1.8152	1.249	0.5662	31.19215513	
					30.12770387
Bag 5					
Chip 1	0.702	0.5426	0.1594	22.70655271	
Chip 2	1.3691	0.9003	0.4688	34.2414725	
Chip 3	1.1158	0.793	0.3228	28.92991576	
					28.62598032
Bag 6					
Chip 1	0.8804	0.6456	0.2348	26.66969559	
Chip 2	1.7109	1.1564	0.5545	32.40984277	
Chip 3	0.8808	0.5595	0.3213	36.47820163	
					29.78277385

Day 3						
Bag 1 (4am)	Before	After	Oil	Oil %		
Chip 1	1.1293	0.9125	0.2168	19.19773311		
Chip 2	0.7998	0.5808	0.219	27.38184546		
Chip 3	1.2676	0.9286	0.339	26.74345219		
					24.44101025	
Bag 2 (4 am)						
Chip 1	1.1257	0.8163	0.3094	27.48512037		
Chip 2	1.2035	0.8503	0.3532	29.34773577		
Chip 3	1.6811	1.2652	0.4159	24.73975373	27.19086996	
Bag 3 (6 am)						
Chip 1	0.9084	0.6631	0.2453	27.00352268		
Chip 2	0.6914	0.5053	0.1861	26.9164015		
Chip 3	1.4474	0.9277	0.5197	35.90576206		
					29.94189541	
Bag 4 (6 am)						
Chip 1	1.4092	1.0373	0.3719	26.39086006		
Chip 2	1.9612	1.4305	0.5307	27.05996329		
Chip 3	2.0177	1.4106	0.6071	30.08871487		
					27.84651274	
Bag 5						
Chip 1	0.6863	0.5006	0.1857	27.05813784		
Chip 2	1.5467	1.0867	0.46	29.74073835		
Chip 3	1.4492	1.0911	0.3581	24.71018493		
					27.16968704	
Bag 6						
Chip 1	1.3733	1.0071	0.3662	26.66569577		
Chip 2	1.7588	1.2775	0.4813	27.36524903		
Chip 3	0.9788	0.7023	0.2765	28.24887617		
		32			27.33609707	
					Overall Average =	**29.11040513**

C2.3 Graphical Representation Plant Scale Experiments:



Appendix D. Quality Control Data:

D.1 Historical Oil Absorption Data

	Canola	Corn	Blend
1	34.75	35.65	36.86
2	37.48	34.13	37.16
3	36.58	32.15	39.63
4	36.58	33.07	39.7
5	33.5	35.68	32.38
6	36.46	31.38	32.12
7	35.72	32.87	37.16
8	37.95	36.42	30.48
9	34.71	28.16	39.51
10	38.6	30.41	40.28
11	36.76	32.73	41.95
12	34.93	36.5	36.22
13	37.87	34.21	30.48
14	35.83	32.84	40.85
15	38.68	31.17	38.39
16		32.7	40.37
17		32.25	39.65
18		31.45	41
19		29.96	34.81
20		32.95	43
21		32.94	37.77
22		31.23	36.51
23		32.4	41.33
24		31.28	32.4
25		34.2	33.78
26		33.48	38.15
27		35.11	32.5
28		28.82	37.72
29		34.75	40.54
30		35.14	33.39
31		30.12	31.82
32		33.49	32.48
33		30.79	36.7
34		31.8	37.48
35		35.7	38.67
36		35.91	38.25
37		33.34	35.89

38		34.54	33.72
39		35.65	35.04
40		31.12	36.44
41		31.36	42.53
42		30.87	38.43
43		33.24	35.36
44		31.5	33.61
45		36.43	39.92
46		32.83	37.21
47		30.3	35.79
48		28.34	41.72
49		36.74	39.04
50		31.62	38.83
51		32.11	38.28
52		33.98	40.9
53		32.62	36.46
54		31.94	39.73
55		34.88	37
56		31.17	36.03
57		30.13	36.1
58		37.15	40.05
59		35.41	37.73
60		29.48	37.51
61		27.86	37.76
62		30.46	37.32
63		29.29	
64		32.42	
65		32.1	
66		32.9	

63		29.29	
64		32.42	
65		32.1	
66		32.9	
67		33.33	
68		32.89	
69		29.03	
70		30.35	
71		29.87	
72		31.87	
73		34.14	
74		33.02	
75		37.39	
76		33.72	
77		36.31	
78		35.32	
79		32.63	
80		32.67	
81		35.41	
82		36.03	
83		33.02	
84		34.97	
85		33.57	

D.2 Graphical Representation of Quality Control Data: