Chapter 3

Vegetable Oil-Based Engine Oils: Are They Practical?

Joseph M. Perez

Tribology Group, Chemical Engineering Department, The Pennsylvania State University, University Park, PA 16802

Introduction

Vegetable oils were the primary lubricants for machinery and transportation vehicles for thousands of years until the discovery of petroleum. Petroleum, primarily on the bases of lower cost and improved performance, quickly replaced vegetable oils as the lubricant (1). Now, with increased petroleum costs, decreased petroleum reserves, and environmental concerns as major factors, vegetable-based oils for lubricants are making a slow but steady comeback. In the past decade, the initial applications have been niche markets such as chain saws, track lubricants, and other total loss lubricants. In Europe, legislation has helped to expand the use of vegetable-based lubricants to the hydraulic fluid market, a potentially large market for biodegradable vegetable oils and synthetic fluids. Looking ahead, the engine oil market is a larger market, one in which vegetable-based lubricants might achieve penetration. However, are vegetable oil-based engine oils practical?

The 2004 *Soy Products Guide* (2), a listing of commercially available industrial products made from soybeans, lists only three companies selling hydraulic fluids and six selling engine oils containing soybean oil. There are a number of companies selling "biodegradable" or "environmentally friendly" hydraulic fluids but these contain other oils such as rapeseed, canola, or synthetic oils. Of the six companies selling engine oils, three sell the same product. There is at least one additional company selling engine oil based on sunflower oil. None of the products have undergone the Society of Automotive Engineers (SAE)/American Society of Testing Materials (ASTM) engine oil test series required to receive American Petroleum Institute (API) certification. Of the vegetable oils on the market, limited field test data are available. There are a number of factors that must be considered to determine whether vegetable oils are practical, including whether they can match the performance required to displace petroleum-based engine oils.

Available Vegetable Oil. In the United States, the major source of in-house vegetable oil for lubricant applications is soybean oil. The total estimated supply of soybeans in 2004 was 2.9 billion bushels; of these, 1.6 billion bushels were crushed to supply 18 billion pounds (2.3 billion gallons) of oil (3,4). Most of this oil enters the food chain and only ~10% is available for use in plastics, solvents, coatings, printing inks, adhesives, and some lubricants. Another competitor for this oil is the growing biodiesel fuel market. Even by blending vegetable oil with synthetics, to control low temperature characteristics of the basestocks, other oils such as sunflower, canola, corn, or palm oil may be needed to have a significant effect on the market. This could result in a continued dependence on foreign oil, but from different sources such as Canada, Brazil, and Indonesia.

Engine Oil Market Size. In 2002, 46% of the 2.4 billion gallons of lubricants sold in the U.S. market were crankcase oils; 13% were transmission, hydraulic fluids, and other automotive oils (5). Various industrial oils make up the remaining 41% of the lubricant market. With current farm production, only ~10% of this market could be supplied by vegetable oil products.

Foreign Oil Replacement. One frequently stated advantage of using renewable lubricants is the replacement of petroleum-based products. Any displacement of petroleum oil affects the balance of payments. Use of renewable lubricants in crankcase oils would result in a small but positive displacement. The total use of petroleum in the U.S. in 2005 was projected to be ~23 million barrels/d. The U.S. transportation demands were projected to use ~55% of the total or >13 million barrels of oil/d (6,7). Basestocks for use in lubricants comprise a small but significant quantity. From each 42-gallon barrel of oil processed, 1.2% is used for lubricants. However, in 2002, the automotive lubricant market alone was >2.4 billion gallons (57 million bbls).

Basestock Cost. Economics is a major factor in the market growth of new products. The cost of vegetable base oils exceeds the current petroleum base oil price of $1.5/gallon by at least 50%. As the price per barrel of oil increases the difference becomes smaller. However, it will take years to significantly reduce the cost differences. If the size of the market increases, the cost of the vegetable base oil will decrease. However, the engine oil market will not increase significantly without API certification, and running the required bench and engine tests will not occur until the market increases. The drivers to produce vegetable-based engine oil lubricants include environmental concerns, improved performance, increased value for farm products, jobs, and the world's disappearing petroleum reserves.

Environmental Concerns. Currently, the major driver in many countries of the world is the concern over air, water, and soil contamination by petroleum products. In many European countries, these concerns have resulted in regulations that require the use of biodegradable lubricants in hydraulic systems of equipment used in forestry and waterways projects. In the United States until recently, no such federal regulations existed outside of Presidential Directives. Some states are requiring the use of low levels of biodiesel, but no hydraulic or engine oil regulations currently exist. However, the 2002 Farm Bill (Farm Security and Rural Investment

Act, published January 11, *Federal Register*), Section 9002 includes language directing all federal government agencies to give preference to "biobased" products, unless it is unreasonable to do so, based on price, availability, or performance. Lubricants are one category specified in the guidelines to be published. The USDA's Office of Energy Policy and New Uses was delegated the authority to implement Section 9002 (8).

Lubricant loss to the environment is another concern. Reportedly, this is the fate of >60% of all lubricants (9). Some obvious areas for increased use of biodegradable hydraulic fluids and engine oils are construction, forestry, farming, and waterways where losses directly affect the environment. Spill cleanup costs in some states are significant. The use of biodegradable lubricants can reduce these costs. Reduction in cleanup costs neutralizes the increased cost of using biodegradable hydraulic fluids made from renewable resources.

For waterways, biodegradable 2-cycle or 4-cycle engine oil lubricants are currently available for use in motorboat engines used on our many lakes and rivers. The 2-cycle oil market is ~2% of the total lubricant market.

Environmentally, biodiesel is a separate issue but it does affect the availability of vegetable oils for lubricants. Diesel engines are more efficient than gasoline engines. This results in a reduction in greenhouse gases. The need to reduce diesel particulate emissions has led to the widespread use of biodiesel. Use of B20 and vegetable-based lubricant results in reduced particulates and possibly a change in the morphology of the particulates. This is discussed elsewhere in detail in the literature (10–12).

Performance Requirements

The major concern of original equipment manufacturers (OEM) is whether the lubricants made with vegetable-based oils are going to give equivalent performance to petroleum products currently in use. This affects engine and equipment durability and warranty costs. Some of the desired fluid properties for hydraulic fluids and engine oils are found in Table 3.1. Of these, oxidation stability and low temperature fluidity are known weak links for vegetable-based stocks. Engine oil performance requirements are more severe than hydraulic fluid requirements due to differences in the operating conditions. In hydraulic system applications, fluid compressibility, hydrolytic stability, foam, and air entrainment requirements are the more important properties. In an engine, oil oxidation stability, deposit formation, friction, and wear are the major concerns. Low temperature fluidity is critical to both applications.

Engine Oil Specifications

The requirements for engine oils are well defined in ASTM and SAE specifications (13–16). SAE J300 defines the viscosity requirements for the various viscosity grades (Table 3.2). ASTM Method D455 is used to define the kinematic viscosity.

TABLE 3.1
Desired Fluid Properties

Automotive lubricants	Hydraulic fluids
High temperature oxidation and thermal stability	Oxidation stability
Temperature-Viscosity (VI)	Viscosity (ISO 32/42)
Low temperature fluidity	Low temperature fluidity
Control friction and wear	Control friction & wear
Suspend contaminants/cleanliness	Control contaminants/cleanliness
Acidity/rust	Hydrolytic stability
Foam control	Foam/air entrainment control
Component compatibility	Component compatibility
Fuel compatibility	Fluid compatibility
Volatility	Volatility
Environment, safety, and health	Environment, safety, and health
Cost	Cost

[a]VI, viscosity index; ISO, International Organization for Standardization.

To simulate viscosity of an operating engine, ASTM High Temperature High Shear Method D4624 is used. ASTM D4684 Mini-Rotary Viscometer Method defines low-temperature pumping properties. Some military requirements are found in Table 3.3.

There are vegetable-based engine oils available on the current market. The basestock of some oils is essentially all vegetable oils and others are blends of vegetable oils and petroleum or synthetic basestocks. In an earlier study by Cheenkachorn at Penn State (17), a number of the oils obtained did not meet their stated viscosity grade as specified in SAE J300. It is more significant that none were API certified.

TABLE 3.2
Society of Automotive Engineers (SAE) Viscosity Requirements-J300/95

SAE viscosity grade	Pumping Max cP at (°C)	Kinematic viscosity cSt at 100°C		HTHS[a] (min) cSt at 150°C and 10^6 s^{-1}
		min	max	
5W	60,000 at (–35)	3.8	—	—
10W	60,000 at (–30)	4.1	—	—
15W	60,000 at (–25)	5.6	—	—
20W	60,000 at (–20)	5.6	—	—
25W	60,000 at (–15)	9.3	—	—
20	—	5.6	<9.3	2.6
30	—	9.3	<12.5	2.9
40	—	12.5	<16.3	2.9
50	—	16.3	<21.9	3.7

[a]HTHS, high temperature high shear.

TABLE 3.3
Military Requirements

Requirement	10W	30	40	5W30	10W30
Pumping viscosity cP max at (°C)	30,000 at (–25)	—	—	30,000 at (–30)	30,000 at (–25)
cSt Viscosity at 100°C min/max	4.1/<7.4	9.3/<12.5	12.5/<16.3	9.3/<12.5	9.3/<12.5
VI, min	—	80	80	—	—
HTHS, cP, min	2.9	—	—	2.9	2.9
Pour point, °Cmax	–30	—	—	–35	–30
Flash point, °C COC, min	205	220	225	200	205
Evaporation, %max	18	—	—	20	17

[a]Abbreviations: VI, viscosity index; HTHS, high temperature high shear; COC, Cleveland Open Cup.

To be certified requires a number of fired engine tests and bench tests. The requirements for gasoline engine oils are discussed elsewhere (18). For diesel engines, the current API CI-4 engine oil requires eight fired engine tests and seven new and used oil bench tests found in Tables 3.4 and 3.5. The number of engine tests for certification has increased from two (CD Oil) to eight (CI-4 oil) as requirements for improved quality have increased in the past 50 years.

Conducting development and certification tests on crankcase oils exceeds 1000K. The time for recovery of investment on these costs is now ~5 years before the next generation of oil must be certified. The target for PC-10, the next generation of diesel engine oils is 2007. CI-4 certifications started in 2002.

Vegetable Oil Properties

The advantages and weaknesses of vegetable oils for lubricant applications are well known (Table 3.6). Vegetable oils have improved lubricity and natural viscosity-

TABLE 3.4
Fired Engine Test for American Petroleum Institute (API) CI-4[a]

Performance requirement	Engine test
Ring, liner, bearing wear and oil consumption	Mack T-10 (EGR)
Ring, valve train wear, filter pressure	Cummins M11-EGR
Differential and sludge content	
Roller-follower wear	GM 6.5 Liter
Piston deposits and oil consumption, two-piece piston	Caterpillar 1R SCTE
Piston deposits and oil consumption, aluminum piston	Caterpillar 1K or 1N SCTE
Engine oil viscosity control due to soot	Mack T-8E
Oil aeration control	International 7.3 L
Oil oxidation	GM 3.8 Liter Sequence IIIF

[a]Abbreviations: EGR, exhaust gas recirculation; SCTE, single cylinder test engine.

TABLE 3.5
Bench Tests for American Petroleum Institute (API) CI-4

Performance characteristics	Bench test
Shear stability	Bosch injector – ASTM[a] D3945
High temperature high shear (HTHS)	ASTM D4683
Volatility	NOACK–ASTM D5800
Low-temperature pumpability	Used oil containing 5% soot from Mack T10–MRV TP-1, ASTM D4684
Elastomer compatibility	ASTM D471
Corrosion control	ASTM D5968
Foaming	ASTM D892

[a]ASTM, American Society of Testing Materials.

temperature properties compared with petroleum-based mineral oils. However, serious negative characteristics of vegetable oils are poor oxidation stability and low-temperature properties. Also of concern are corrosion and hydrolytic stability. Research in the 1990s by a number of organizations including ADM, Cargill, Dow, Dupont, Lubrizol, Penn State, Renewable Lubricants, the USDA (Food & Industrial Oil Research Unit, Peoria, IL), and others was aimed at improving these weak links. Research focused on using additive technology, chemical modifications, genetic engineering, and blending with other biodegradable synthetic fluids.

Oxidation Stability. Basically, the key to oxidation stability is chemical structure. The more oleic double bonds in the fatty acid chains of the triglyceride, the better the oxidation stability. The more conjugated double bonds in the fatty acid chain the poorer the oxidation stability. Typical vegetable fatty acids are oleic, linoleic and linolenic, Figure 3.1. The relative rates of reactivity are found in Figures 3.2 and 3.3. The composition varies depending on the source, Table 3.7. Studies have shown that oxidation stability can be improved by the use of selected additives,

TABLE 3.6
Vegetable Oils

Advantages		
Environmental	Properties	
Biodegradable	Low volatility	
Renewable	Viscosity-Temperature (High viscosity index)	
Nontoxic	Friction and wear	
Disadvantages or unresolved issues		
Environmental	Properties	Other
Oxidation issues	Low temperature	Cost
	Oxidation stability	Volume
	Hydrolysis	Quality

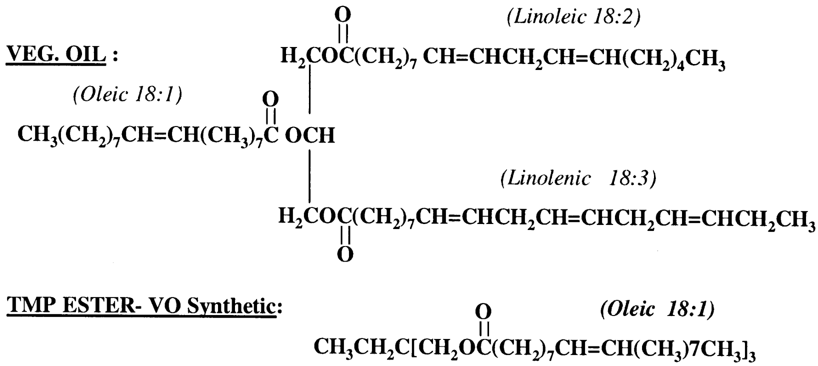

Fig. 3.1. Vegetable oil structures.

genetic engineering and chemical modifications. However, some of these improvements result in poor low-temperature properties. These properties can be improved by blending the vegetable oils with low pour point basestocks that have acceptable biodegradability. In some cases, chemical modification, such as alkylation and esterification with selected polyol alcohols, can also improve low-temperature properties.

Engine Oil Status

Currently, a few small companies are marketing 2- or 4-cycle vegetable-based engine oils on a limited basis, and some major companies have active research in progress in this area. Companies in the United States that are marketing 4-cycle vegetable oil-based engine oils include Agro Management Group of Colorado

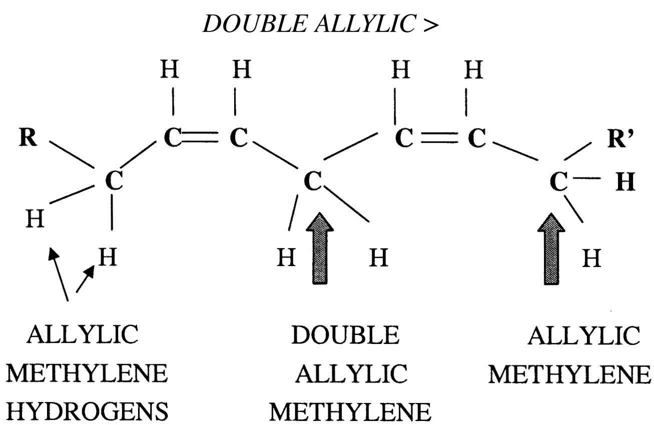

Fig. 3.2. Relative reactivity of hydrogens in vegetable oils.

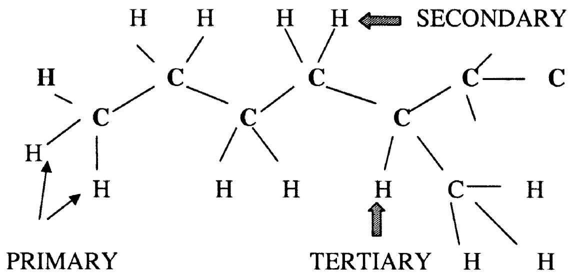

Fig. 3.3. Order of reactivity of hydrogens: ALLYLIC >> TERTIARY > SECONDARY > PRIMARY.

Springs, CO (AGM) and Renewable Lubricants (RLI) of Hartsville, OH. Others such as Penn State and the USDA Food & Industrial Oil Research Unit are conducting research aimed at understanding and improving the performance of these oils. Lubrizol was one of the early leaders and focused on additive chemistry. Other major lubricant and additive suppliers have active programs. Valvoline, a Division of Ashland Chemical, is one of the leaders in this area and has shared some of the progress and problems in the development of vegetable-based engine oils (19).

The Agro Management Group developed a canola-based 4-cycle engine oil in the early 1990s. The oil (AGM 2000) was evaluated in various vehicles by AGM including tests on ~75 vehicles operated by the U.S. Postal Service in the state of Michigan. Results of these tests were reported earlier (18). According to the authors, Rhodes and Johnson, vegetable-based oils performed well in well-managed fleets, resulting in a significant reduction in emissions and improved engine performance.

RLI collaborated with the Tribology Group, Chemical Engineering Department of Penn State in the early 1990s to develop vegetable-based engine oils. Various vegetable oils were evaluated including genetically modified high-oleic vegetable oils (20–23). An understanding was developed regarding the mechanism of oxidation and

TABLE 3.7
Composition of Soybean Oils

Composition	Normal soybean (%)	Genetically modified (%)	Epoxidized (%)	TMP[a] (Oleic) (%)
18:0	15	11	(100)	0
18:1	23	83	0	100
18:2	53	3	0	0
18:3	7	2	0	0
TOTAL-C=C- per 100 molecules	150	95	0	100

[a]TMP, trimethylolpropane.

the formation of deposits. A high-oleic basestock containing a unique additive package was tested in several RLI vehicles for several years. Vehicles included a 3.8 L Oldsmobile engine, a flex-fuel Ford Taurus, a 3500 HP ethanol drag racing funny car and a three-quarter ton Ford pickup diesel truck. The vehicles accumulated >200,000 miles, and some test results were reported previously (24). This resulted in one of the first U.S. patented 4-cycle vegetable-based engine oils (25) and subsequently resulted in several additional biobased lubricant patents by RLI (26,27). Research by RLI has continued, and currently a fleet of 17 vehicles are being tested. RLI has an excellent track record with their fluids and is one of the leaders in vegetable oil technology (www.renewablelube.com).

The Food & Industrial Oil Research Unit, National Center for Agricultural Research Unit, Agricultural Research Service, USDA in Peoria, IL and Penn State University have collaborated in studying industrial uses of vegetable oils since the late 1990s. This research resulted in various products and one patent but more importantly in an understanding of the chemistry affecting oxidation stability and low-temperature properties (28–32).

Valvoline, a division of Ashland Chemicals, is aggressively pursuing the use of vegetable oils in engine oils. They are currently testing mid-oleic soybean oil for use in crank formulations. The project involves full bench test screening of formulas containing soybean oil and other basestocks. The formulations contain additives used in the latest engine oil categories. One of the benefits seen is cost reduction for new oils that would come from a reduction in the use of expensive Group III and II+ petroleum basestocks required to meet NOACK volatility requirements. Cold crank properties, high viscosity index (VI; temperature-viscosity properties), and friction and wear benefits are drivers in this ongoing study (19).

Summary

Can vegetable oils make good engine oil basestocks? The research conducted to date indicates that chemically and genetically modified vegetable oils have excellent potential to perform adequately in engine oils. Some technical and logistic concerns remain regarding the ability to maintain consistent quality oils that would meet oil property and performance specifications. Limited data exist on the blending of vegetable oils; to produce adequate volumes, “refineries” using different vegetable oils and producing various products will be required. Currently, the publication, *Physical and Chemical Characteristics of Oils, Fats and Waxes* (33), lists 350 oils that could be considered for use as engine oil basestocks.

The bottom line is that vegetable oils have shown acceptable property and performance characteristics. However, to make a major penetration of the engine oil market in the next 10 years as a major competitor for petroleum-based engine oils, certification must be obtained by passing the current automotive engine performance tests. These are very expensive and must be justified by a large market. Therefore, at the present time, the chicken and egg syndrome persists.

References

1. Dowsan, D., *History of Tribology*, Longman Group, Ltd., New York, 1979.
2. United Soybean Board, *Soy Products Guide*, www.unitedsoybean.org, 2005.
3. Campen, J., "USB Overview," Lubricants Technical Advisory Board Presentation, Chicago, IL, Sept. 22, 2004, www.unitedsoybean.org.
4. Erhan, S.Z., The Use of Vegetable Oils as Lubricants, in *Bailey's Industrial Oil and Fat Products*, 6th ed., John Wiley & Sons, New York, 2004.
5. Lubricants Industry Sourcebook, *Lubes'n'Greases*, 2004–2005.
6. Transportation Energy Book: Edition 21,DOE/ORNL-6966.
7. Energy Information Administration *Annual Energy Outlook 2002*, DOE/EIA-0383 (2002), December, 2001.
8. ron.buckhalt@nps.ars.usda.gov.
9. McFall, D., Almost 1.5 Billion Gallons, *Lubes'n'Greases 10*: 6 (November 2004).
10. Boehman, A.L., W.H. Swain, D.E. Weller, and J.M.Perez, Use of Vegetable Oil Lubricant in a Low Heat Rejection Engine to Reduce Particulate Emissions, SAE Technical Paper 980887, Detroit, MI (February 1998).
11. Weller, D.E., W.H. Swain, H. Hess, A.L. Boehman, and J.M. Perez, Changes in Particulate Composition and Morphology When Using Vegetable Oil Lubricant in a Low Heat Rejection Engine, SAE Technical Paper No. 1999-01-0975.
12. Perez, J.M., and A.L. Boehman, Environmentally Friendly Fuels and Lubricants, in *Biobased Industrial Fluids and Lubricants*, edited by S.Z. Erhan and J.M. Perez, Ch. 6, AOCS Press, Champaign, IL, 2002.
13. SAE Recommended Practice J300, *SAE Handbook*, Society of Automotive Engineers, Warrendale, MI.
14. ASTM D4684, Standard Test Method for the Determination of Yield Stress and Apparent Viscosity in Engine Oils at Low Temperatures (1994), ASTM, West Conshohocken, PA 19428-2959.
15. ASTM 5481, Standard Test Method for Measuring Apparent Viscosity at High Shear Rate by Multicell Capillary Viscometer (1994), ASTM, West Conshohocken, PA 19428-2959.
16. ASTM D445, Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids—the Calculation of Dynamic Viscosity (1988), ASTM, West Conshohocken, PA 19428-2959.
17. Cheenkachorn, K., A Study of Environmentally Friendly Lubricants for Automotive Engine Oils, M.S. Thesis, The Pennsylvania State University, May 1999.
18. Rhodes, B.N., and D. Johnson, Vegetable-Based Motor Oils, in *Biobased Industrial Fluids and Lubricants*, edited by S.Z. Erhan and J.M. Perez, Ch. 8, AOCS Press, Champaign, IL, 2002.
19. McCoy, S., Valvoline Engine Oil Development, *Proceedings of the 9th United Soybean Board Lubricants and Fluids Technical Advisory Panel Meeting*, Ch. 8, Chicago, IL, September 22, 2004.
20. Asadauskas, S., J.M. Perez, and J.L. Duda, Suitability of Basestocks for Biodegradable Lubricants, *Petroleum Division Preprints*, Vol. 42, No. 1, Feb. 1997, presented at 213th ACS Meeting, San Francisco, CA, April 15, 1997.
21. Asadauskas, S., J.M. Perez, and J.L. Duda, Oxidative Stability and Antiwear Properties of High Oleic Vegetable Oils, *Lubr. Eng. 52*: 877–882 (December 1996).

22. Asadauskas, S., J.M. Perez, and J.L. Duda, Lubrication Properties of Castor Oil—Potential Basestock for Biodegradable Lubricants, *Lubr. Eng. 53*: 35–40 (December 1997).
23. Perez, J.M., S. Asadauskas, and W.W. Garmier, Vegetable Based Engine Oils, presented at 52nd Annual STLE Meeting, Kansas City, MO, May 29, 1997.
24. Garmier,W.W., Vegetable Oil Stabilization, *Proceedings of the 4th United Soybean Board Lubricants and Fluids Technical Advisory Panel Meeting*, Chicago, IL, September 1999.
25. Garmier,W.W., U.S. Patent No. 5,736,493 (1998).
26. Garmier,W.W., U.S. Patent No. 5,863,872 (1999).
27. Garmier,W.W., U.S. Patent No. 5,990,055 (1999).
28. Adhvaryu, A., S.Z. Erhan, and J.M. Perez, Oxidation Kinetic Studies of Unmodified and Genetically Modified Vegetables Using PDSC and NMR Spectroscopy, *Thermochim. Acta 364*: 87–97 (2000).
29. Asadauskas, S., and S.Z. Erhan, Depression of Pour Points of Vegetable Oils by Blending with Diluents Used for Biodegradable Lubriants, *J. Am. Oil Chem. Soc. 76*: 313–316.
30. Weller, D.E., Jr., and J.M. Perez, The Effect of Chemical Structure on Friction and Wear, *Lubr. Eng. 56*: 39–44 (November 2000).(AQ3)
31. Weller, D.E., Jr., and J.M. Perez, A Study of the Effect of Chemical Structure on Friction and Wear: Part 2 Vegetable Oils and Esters, *Lubr. Eng. 57*: 20–26 (May 2001).
32. Cheenkachorn, K., Ph.D. Thesis, The Pennsylvania State University, May 2003
33. Firestone, D., ed., *Physical and Chemical Characteristics of Oils, Fats and Waxes*, AOCS Press, Champaign, IL (1999).