Vegetable Oil as a Diesel Fuel: Status and Research Priorities

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ABSTRACT

A review of the current status of vegetable oils as a possible substitute for diesel fuel is presented. Topics considered include identification of high oil bearing crops, oil processing and storage, results of short and long term engine tests, use of transesterification of vegetable oils and microemulsions, emissions, economics, and priorities for additional research. Results indicate that highly saturated oils could be used in a blend with diesel in emergencies, however, engine life would be reduced and maintenance costs would be increased. Vegetable oil esters are possibly a direct substitute for diesel fuel; low temperature operation and corrosiveness are problems. Vegetable oil esters are more expensive than petroleum based fuels at the present time. Future research priorities are discussed.

INTRODUCTION

History records that Rudolph Diesel, the inventor of the engine that bears his name, used vegetable oils as a fuel in his engines as early as 1900. For many years, the ready availability of inexpensive petroleum middle distillate fuels provided little incentive for experimenting with alternative, renewable fuels for diesel engines.

The OPEC oil embargo of the '70's, fuel shortages and rapidly escalating fuel prices caused a resurgence of interest in finding alternative fuels. However, the success of oil conservation measures and the very real possibility of some of these alternative fuels being used as a replacement for petroleum fuels have caused petroleum prices to level off and even to decline as supplies have once again exceeded demand. The oil cartel is not nearly as formiddable as it once appeared. Australia, for example, which once was 100% dependent on foreign oil now predicts that they may be 100% self sufficient by the year 2000. This situation is remarkable when it is considered that they first produced oil in commercial quantities just 23 years ago (Quick, 1984).

During the peak of the energy crisis it was not uncommon to hear scientists say that if they had 10 years to work on the problem many of the potential solutions to the energy crisis could be a reality. Now it appears the 10 years may indeed be available; however, it also appears that the public commitment to making use of this time to develop new technologies has waned. A recent survey of program activity among those most involved in vegetable oil fuel technology shows that most programs have been terminated, redirected or are currently working on drastically reduced budgets with little hope new funding sources will become available. As a consequence, the opportunity to provide solutions to problelms associated with use of vegetable oil as a diesel fuel replacement appears bleak indeed.

Agricultural production is especially vulnerable to short term shortages of fuels which are vital to carrying out field operations such as planting, cultivating and harvesting. Timing of these operations is especially cricitcal. With many crops a few days delay can result in reduced yields or even a total loss of the crop. Corn yields, as with many other field crops, are closely related to date of planting. Cultivation, spraying, and thinning must be completed on schedule. The harvest operation is extremely critical such that with crops like sweet corn or tomatoes only a few days difference greatly influences quality. Even in crops such as the cereal grains delays in harvest can result in shattering of the standing crop or increased susceptibility to weather. For all of these operations a continuous, readily available supply of liquid fuels is essential for agriculture to produce the bounteous supply of food to which this country has become accustomed.

It is in the agricultural sector where a backup supply of fuel for diesel equipment is badly needed and it is on the farm where vegetable oil has the best chance of making an impact. A dual technology strategy would provide a valuable oil export crop and would allow that crop to be turned into a liquid fuel guaranteeing agricultural production in a time of emergency. Properly administered, this program would include a wide array of processing equipment expressing the oil for the food and export markets but this same equipment would be ready for channeling oil into the fuel pipeline should an emergency occur.

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As stated above, it has been known that vegetable oil could be used to fuel a compression ignition engine since its very inception. It took the oil crisis to renew that interest. Consequently, serious investigations into the technology of using vegetable oil have only been actively pursued since 1979. This paper will renew the status of research concerned with utilization of vegetable oils as alternative fuels for diesel engines and present research priorities identified by those most closely aligned with the new technology. The various aspects of using vegetable oil as fuel include: crop production and development including selection of high oil bearing crops; oil processing and storage; filtration; blends and additives; transesterification; engine problems with deposits and injector coking; use of by-products; economics of vegetable oil use and potential production of oil seed crops.

IDENTIFICATION OF HIGH OIL BEARING CROPS AND CULTIVARS

Jamieson (1943) lists over 350 oil bearing crops while Duke and Bagby (1982) listed 70 species of oilseed crops with production potential. Seed yields ranged from 200 to 14000 kg/ha; they say, "the low one is too low to be considered and the high one suspiciously high." A listing of these potential oilseed species is given in Appendix 1. The most predominantly considered of these as fuel substitutes are sunflower, safflower, soybean, cotton, winter rape, canola, and peanut. In 1981, 14.7% of U.S. cropland was devoted to soybeans, 3.1% to cottonseed, 0.8% to sunflower, and 0.3% to peanuts. Each of the other species were produced in very small quantities.

Table 1 compares some of the fuel properties of some vegetable oils and esters with diesel No. 2. All of the vegetable oils have energy contents very similar to diesel (94% of the energy content on a volume basis), but vegetable oils are 11 to 17 times more viscous. This high viscosity causes injector spray pattern problems and is thought to be at least in part responsible for the difficulties experienced with engine deposits. The vegetable oils listed have nearly the same specific gravity, but all are seven to nine percent heavier than diesel. Bettis et al. (1982) demonstrated that the variation in viscosity was due to the fatty acid chain length, the number of unsaturated bonds and the interaction between these two components.

TABLE 1. SPECIFIC GRAVITY, VISCOSITY AND HEAT OF COMBUSTION OF SELECTED VEGETABLE OILS AND NO. 2 DIESEL (TYPICAL VALUES)

Oil type	Specific gravity		Kinematic viscosity		Heat of combustion	
	g/mL	ratio*	mm^{2}s	ratio*	kJ/kg	ratio*
Sunflower	0.92	1.08	34.9	12.0	39644	0.87
Lin. saff.	0.93	1.09	32.3	11.1	39226	0.86
Oleic saff.	0.92	1.08	42.1	14.5	39306	0.87
Soybean	0.92	1.08	36.4	12.6	39390	0.87
Cottonseed	0.91	1.07	37.4	12.9	37420	0.82
Peanut	0.91	1.07	37.2	12.8	37160	0.82
LEAR 1	0.92	1.08	39.0	13.4	39913	0.88
HEAR 2	0.91	1.07	51.0	17.6	40167	0.88
SBME 3	0.88	1.04	4.1	1.4	39796	0.88
SSME 4	0.88	1.04	4.8	1.6	37690	0.83
No. 2 Diesel	0.85	1.00	2.9	1.0	45390	1.00

* ratio relative to No. 2 Diesel
1 LEAR = low erucic acid rapeseed
2 HEAR = high erucic acid rapeseed
3 SBME = Methyl ester of soybean oil
4 SSME = Methyl ester of sunflower oil

Research directed to improving species, improving quantity and quality of seed yield, and improving production techniques has a vast potential for improving potential oil production. Many of these species have received little or no attention from the scientific world. Loeffelman and Auld (1985) have demonstrated with winter rape that a great potential exists for modifying the fatty acid constituency of the oil through modern techniques of biotechnology. They have identified the properties needed for food, industrial and fuel grade oils and developed plants selected specifically for each of these uses. They have also demonstrated the genetic potential of winter rape by demonstrating yields in research plots as much as 3 times those commonly produced commercially. Similar activity is underway with other potential oil crops in other parts of the U.S. and the world. It is not unreasonable to believe that greatly improved production will result as it has in crops such as corn and wheat where a very intensive production effort has been in place for many years.

Fatty acid content of vegetable oil has been found to be a significant factor in reducing carbon buildup in the engine. Oils with a lower level of unsaturation are more highly desirable for fuels. Vegetable oils are fatty esters of glycerol (triaglycerides) and have the chemical structure as shown in Fig. 1.:
Where R_1, R_2, and R_3 represent the hydrocarbon chain of the fatty acids. R_1, R_2, and R_3 may be the same, depending upon the particular oil, but ordinarily are different in chain length and in the number of double bonds present. Shorthand notation for fatty acid consists of two numbers, separated by a colon; the first indicates the total number of carbon atoms, the second the number of double bonds. The most commonly encountered fatty acids are (Pryde, 1981):

lauric 12:0
palmitic 16:0
stearic 18:0
oleic 18:1
linoleic 18:2
linolenic 18:3
erucic 22:1
ricinoleic 18:1

All are found in different amounts in vegetable oils, except for ricinoleic which occurs only in caster oil and erucic which occurs in rapeseed and crambe. Table 2 lists the major fatty acid constituents of a few vegetable oils.

Loeffelman and Auld (1985) use a Fuel Index Value

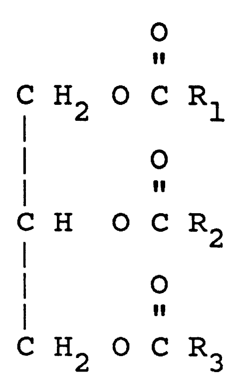

Fig. 1—Vegetable oil's structural notation.

TABLE 2. FATTY ACID COMPOSITION OF VEGETABLE OILS (TYPICAL VALUES)

	Palmitic 16:0	Stearic 18:0	Oleic 18:1	Linoleic 18:2	Eicosenoic 20:1	Linolenic 18:3	Erucic 22:1
			% by weight methyl esters				
L. saff.	5.9	1.5	8.8	83.8			
O. saff.	4.8	1.4	74.1	19.7			
O. rape	4.3	1.3	59.9	21.1		13.2	
E. rape	3.0	0.8	13.1	14.1	7.4	9.7	50.7
Soybean	10.8	4.1	23.0	52.7		7.6	
Sunfl.	6.2	4.2	17.8	71.6			
Peanut	6.3	4.9	60.6	21.6			

(FIV) for selecting fuel cultivars of winter rape as follows:

$$\text{FIV} = 1\ (\%\ \text{oleic acid}) + 4\ (\%\ \text{linoleic acid}) + 8\ (\%\ \text{linolenic acid}) + 1.1\ (\%\ \text{eiconsenoic acid}) + 1.2\ (\%\ \text{erucic acid})$$

This equation was developed from observations on the general importance of fatty acidd composition on engine deposits from tests reported in the literature using a number of types of vegetable oils. The validity of the equation has not been verified experimentally.

Transesterification

Transesterification is the process of reacting a triglyceride, such as one of the vegetable oils, with an alcohol in the presence of a catalyst to produce glycerol and fatty acid esters. The molecular weight of a "typical" ester molecule is roughly one third that of a straight vegetable oil molecule and has a viscosity approximately twice that of diesel fuel instead of 10 to 20 times, as is the case for the neat vegetable oils (Table 1). Since viscosity of the fuel is of prime concern because of its effect on the diesel injection system and resulting spray patterns, the resulting reduction in viscosity greatly reduces engine operation problems. Wagner et al (1984) states, "Ethyl, methyl and butyl esters with and without commercial diesel fuel additives have fuel properties that are comparable with diesel fuel. The high gum content developed . . . is undesirable from the standpoint of the ester fuels' shelf life and fuel filter plugging problems." Some of their specific observation are:

1. The pour points and cloud points are much higher than diesel indicating that the esters are much more susceptible to problems when used in cold weather. Pour point improvers provided a slight drop in the case of methyl and ethyl esters. They suggest additional experimentation in this area.
2. Higher flash points make them somewhat safer to handle than diesel fuel.
3. The transesterification process raises the cetane to a level comparable to or better than diesel fuel.
4. The higher or gross heating value of the esters was approximately 11% lower than diesel on a mass basis.
5. The specifc gravity of the esters was somewhat higher than diesel; an average of 0.881 compard to 0.847 for the reference diesel fuel. Thus on a volume basis the energy content of the ester is somewhat closer to diesel than on a mass basis.

OIL PROCESSING AND STORAGE

Extraction

Extraction of vegetable oils for food and industrial markets is a common practice, carried on successfully in many locations with a variety of oil sources. Nearly all previous extraction data has been concerned with large scale processing plants. The concept of oil recovery on the farm as inexpensively as possible in order to compete with the price of fuel has been the major point of focus in the alternative fuels research reports. Additional work has included identifying optimum parameters of press operation and processing associated with transesterification.

Three methods of removing the oil from the oil seeds are currently in use. First, the solvent extraction process in which the crushed oil seeds are soaked in a solvent such as hexane. The meal is removed and the hexane evaporated leaving the oil. The complexity and hazards associated with solvent extraction have generally been considered undesirable for small on-farm processing plants. However, hexane extraction is a likely method for larger plants. A second method of extracting oil is through use of a mechanical screw press. The third, method combines solvent extraction with a light screw pressing operation. The third method is the most likely approach for larger plants and is the general method used for most commercial oil seed expression plants. The second method, simple scrwpressing, has been considered the most likely candidate for on-farm use.

The mechanical screwpress has five elements: the main worm shaft and worm drainage barrel; choke mechanism; motor, transmission and bearings; and the loading system. The press is designed to exceed a pressure of 1000-1400 kg/cm^2 on the seed and should reduce the oil content from 42 to 45% in whole seed to 14 or 15% in processed meal. For this reason, small screwpresses are less satisfactory for the oil seeds having lower oil percentages of 18 to 20% such as soybeans than they are for peanuts, rapeseed and safflower which have oil percentages of 40 to 50%. Power requirements are approximately one kw per metric ton of daily capacity. Seed is generally preheated at a temperature of 50°C to 100°C with holdup times of 15 to 20 min. Most research on optimizing seed temperature for use with a small press has reported temperatures on the low end of the scale to be adequate. Goodrum and Sivakumarin (1965) however, report extraction of 91% of the oil by optimizing the conditions. They found a temperature of 95.6°C, 5.42 % moisture and 27.4 minimum preheat time to be optimum for peanuts.

To complete an on-farm processing system, equipment needed in addition to the press and preheater includes seed, meal and oil holding bins, seed and meal augers, oil pump and filtration equipment.

Filtration

Filtration needed following the expression of the oil consists first, of settling in a holding tank for a minimum of 48 h and then filtering through a series of elements ending with 4 to 5 micron filtration. Also, most vegetable oils have small amounts of phosphatides called "gums" and free fatty acids which are removed by hydrating with steam or hot water. Peterson et al. (1982) used a simple filtration system consisting of throw away filters and a final fuel filter from a diesel engine to filter rape oil. They also found the washing operation to be unnecessary with rape. Most researchers have reported fuel filter plugging to be a problem when using vegetable oil and appropriate precautions should be considered. Wagner (1984) found that the addition of DuPont FOA-2 additive reduced filter plugging fourfold.

Vegetable Oil Storage

Long term storage of vegetable oil has been studied by Korus and Jo (1985) and Klopfenstein and Walker (1985). Each of these studies were of two years duration.

Korus and Jo (1985) used peroxide values as a measure of oxidation. They found peroxide values to be constant in anaerobic storage. All samples were stored in glass containers. The anaerobic samples were prepared by purging with nitrogen gas and sealing with an air tight cap. In aerobic storage they report an initial induction period of 140 to 200 days during which the peroxide values increased very slowly. After the induction period, peroxide values increased linearly. The pattern of viscosity increases during storage were similar to the peroxide values. Viscosities increased only 4 to 6% after two years in anaerobic storage. Both peroxide value and viscosity increases were greater for increasing oil unsaturation in aerobic storage.

Klopfenstein and Walker (1985) stored soybean esters under a variety of conditions in steel or plastic-lined tanks with and without antioxidant. In general they found that lower storage temperatures, presence of antioxidant (BHT at 0.05%) and storage in plastic-lined tanks led to lower peroxide values and less loss of linoleic acid. Samples stored in plastic lined containers had lower peroxide values than similar samples stored in steel containers. Presence of antioxidant resulted in lower peroxide values. Underground storage resulted in very similar peroxide values for all samples. Outside storage was the harshest treatment.

These two studies indicate that vegetable oils could maintain their fuel qualities for long periods if reasonable care were exercised in storage.

ENGINE TESTS

Short Term Engine Tests

Nearly every study performed to data has shown that vegetable oil can be used as a direct substitute for diesel in short term tests limited only by the viscosity of the fuel. In summary, short term tests shown that power output, torque and brake thermal efficiency when engines are fueled with vegetable oil fuels equal or were very close to that when the engine was fueled on diesel, Peterson et al. (1983). Fuel consumption is generally slightly higher reflecting the slightly reduced energy content of the vegetable oil, typical data for 5 vegetable oils is given in Table 3.

TABLE 3. POWER OUTPUT, FUEL CONSUMPTION, SPECIFIC ENERGY AND THERMAL EFFICIENCY OF FIVE VEGETABLE OILS AND NO. 2 DIESEL DURING SHORT TERM ENGINE TESTS, IDAHO DATA

Fuel type	Power, kW	Fuel consumption, kg/h	L/h	Specific energy, kWh/L	Thermal efficiency, %
O. saff.	30.0	10.2	11.0	27.2	27.0
L. saff.	29.5	10.4	11.2	26.4	26.0
O. rape	29.4	10.0	10.9	26.9	26.6
E. rape	29.7	10.2	11.1	26.9	26.5
Sunflower	29.5	10.1	10.9	27.0	26.7
No. 2 diesel	29.5	9.7	11.4	25.9	24.2

Quick (1980) summarized 22 short term engine tests conducted at 12 locations worldwide in which vegetable oil was compared to diesel as a fuel. Peak engine power on the vegetable oil fuels ranged from 91 to 109% of that on diesel fuel. In these tests 16 of the 22 reported peak power equal to or exceeding that when the engines were operated on diesel. The vegetable oils included in the tests were rapeseed, soybean, sunflower, peanut, palm kernel, jojoba, coconut, linseed and canola.

Long Term Endurance Tests—Direct Injection Engines

While short term results are almost always positive, longer term tests almost always lead to severe engine deposits, ring sticking, injector coking and thickening of the lubricating oil.

Injector coking is a problem reported in most long term engine tests with vegetable oils. Vand der Walt and Hugo (1982) report on a number of measures to reduce injector coking with little success from any of them. These include partial retraction of the injector tip, the addition of a heat shield, cooling the injector with water, coating the injector with teflon, increasing the back leakage rates, and increasing the injector temperature. They also report on 26 fuel additives, only a few of which showed any tendency to reduce coking. Other methods of reducing injector coking have been reported by Peterson et al. (1983) where coking was reduced by proper choice of fatty acid and by Mora and Peterson (1985) through use of propane fumigation and transesterification. Many researchers have also reported reduced engine problems through use of the vegetable oil esters (see transesterification above).

A second major problem associated with vegetable oil use in direct injection engines is polymerization of the vegetable oil in the ring belt area causing the rings to seize. This is often associated with an increase in blow-by, a corresponding increase in the viscosity of the lubricating oil and resulting catastrophic failure of the engine. Kaufman (1985) reports that, "If the vegetable oil is to be used without modification in direct injection diesel engines, it would need to be blended with diesel fuel. The blend should not contain more than 25 percent vegetable oil. Whereas, if the vegetable oil is transesterified, it may completely replace diesel fuel. However, reduced engine life may occur in both cases."

Fuls et al. (1984) reports, "Reduction of sunflower oil viscosity by adding 20% petrol resulted in extension of the operational period to 300 h. Injector coking and consequent poor atomization led to sticking piston rings, heavy deposits in the engine and polymerization of the lubricating oil. A large number of fuel additives were tried in attempts to eliminate the coking problem, but without success."

One factor which can reduce the engine deposit problem and somewhat extend engine life is the choice of vegetable oil. Those oils with fewer double and triple bonds in their fatty acids, that is, those less unsaturated vegetable oils, have less tendency to polymerize. Korus et al. (1982) found the relative rate of oxidative polymerization between oleic and linoleic safflower (the extremes of unsaturation) to be 1:3. Relative rates of thermal polymerization of oleic and linoleic safflower were approximately 1:30. They concluded that thermal polymerization may be the dominant gum forming reaction under combustion conditions and that carbon coking could be reduced with a lower degree of oil unsaturation and with better atomization of the fuel. Peterson et al. (1984) compared high oleic safflower and high lonoleic safflower in 200 h EMA test cycles. Engines operated on oleic oils did have somewhat less engine deposits at the conclusion of the tests than did engines operated on the more unsaturated linoleic safflower, but both were high in deposits when compared to those operated on diesel fuel.

German et al. (1985) reported on operating six tractors on North Dakota farms over a three year period with alkali-refined, winterized sunflower oil/No. 2 diesel fuel blends. The engines operated a total of 7616.9 hours and burned a total of 145,891.8 L of fuel. Three tractors were fueled with 25% sunflower oil/75% diesel and three with 50% sunflower oil/50% diesel. All engines were turbocharged, direct injection diesel engines. Two were intercooled and one used a fuel and lubricating oil additive. One engine experienced a camshaft/valve train failure. Most deposits were found on engines fueled with the 50% sunflower oil; a significantly lower level of deposits were found on pistons from engines fueled with 25% sunflower oil. The lowest average amount of deposits were found on pistons from engines fueled with only No. 2 diesel fuel. No injector coking problems or ring sticking problems were encountered. Bearing wear was normal.

German et al (1985) concludes, "Based on this study, use of a 25% sunflower oil/75% No. 2 diesel fuel blend or a 50% sunflower oil/50% diesel fuel blend as a substitute diesel fuel cannot be recommended. However, under emergency conditions, a 25/75 blend of alkali-refined, winterized sunflower oil/diesel fuel could be used as diesel engine fuel, but the operator must be aware that reduced engine life would occur."

Long Term Endurance Tests—Indirect Injection Engines

Problems associated with using vegetable oils have been observed to be much less severe in indirect injection engines, i.e., those with pintle type injectors and precombustion chambers than in their direct injection counterparts. Fuls et al (1984) reports that, "A Duetz F3L912W engine was installed in an agricultural tractor and subjected to extended service life, PTO tests using the manufacturers prescribed duty cycle. The manufacturer's cycle of 1800 h was completed without any problems and no coking was evident . . . The general condition of the engine and components at the completion of the test was such that the manufacturer issued a warranty on their indirect injection engines for operation on sunflower oil."

Fuls (1984) reports that two additional indirect injection engines of different manufacturers are currently under test one has completed 1600 h with little problems. Kaufman (1985) says, "vegetable oil can be used successfully in modified, indirect injection engines, but the worldwide trend in engine design is away from indirect injection engines toward the greater fuel economy of direct injection diesel engines."

Quick and Woodmore (1984) conclude, "Our experience at Glenfield with 200 h tests, even with linseed oil, is that the indirect-injected engines will run vastly longer before problems occur with vegetable oil than will their direct injected counterparts." They caution that there are still questions relating to vegatable oil contaminating the lubricating oil in worn engines and varying oil quality from batch to batch and changes in storage.

Pischinger et al. (1982a) reports on tests with the Passat diesel indirect injection engine which was run 16,000 km on a 30-70 soybean oil-diesel mixture and then 20,000 km on 100 percent peanut oil. They found the combustion chambers to be relatively clean but reported the following problems:

1. High viscosities render some modifications to the fuel system necessary.
2. With peanut oil they found deposits on intake valve stems.
3. Cold starting was harder.
4. The smell of exhaust gases was unbearable.

Peterson et al (1985) reported on long term tests in small indirect diesel engines comparing starting and stopping on diesel fuel with engines operated continuously on vegetable oil. Fuel used on both engines was a 50% winter rape blend with diesel. The engine fueled with 100% diesel at start-up and shutdown operated 50% longer than the engine started and stopped on the vegetable oil mixture (3256 h versus 2406 h). They report that compression and power were within acceptable limits until over a very short period of time engine oil viscosity increased and the engines would no longer start.

Engler and Johnson (1983) found performance curves for processed sunflower and cottonseed oils to be slightly better than for diesel when tested in a small indirect injection engine. But, increased carbon deposits and lubricating oil fouling were noted. They concluded, "Although processed oils may be acceptable fuels for short term use, they are not recommended as alternative diesel fuels at this time."

Exhaust Emissions

Wagner et al. (1984) and Geyer et al. (1984) report on emissions from vegetable oil esters and in the latter case from both vegetable oil esters and from the neat vegetable oils. Generally the gas phase emissions are the same or slightly higher than diesel fuel; however, both report significantly higher NO_x and lower smoke levels for the methyl and ethyl esters compared to diesel fuel. Geyer et al. (1984) reports that the total aldehydes increased dramatically when compared to diesel fuel, the averages of the methyl esters were slightly higher than the neat oils.

Pischinger et al. (1982a) measured CO and NO_x emissions on an IDI Passat vehicle and found CO emission 40% lower and NO_x emission unchanged when fueled with methyl ester of soybean oil compared to diesel.

EMA Test Cycle

Pryde and Schwab (1983) report that the Alternative Fuels Committee of the Engine Manufacturers Association was asked by the USDA's Northern Agricultural Energy Center to develop a suitable screening test that could be used to eliminate the worst fuels more quickly. They report that out of 8 tests conducted, the only fuels passing the test conclusively were the simple esters of either sunflower or soybean oil and the blend of 25 percent high oleic safflower oil in diesel oil. Goering (1984) reports that four hybrid oils also passed the EMA test cycle; but, there were indications that problems may occur in longer tests. Peterson and Wagner (1982) include a copy of the EMA test cycle in the appendix of their ASAE paper.

OIL MODIFICATIONS

Engine Tests with Vegetable Oil Esters

A number of researchers have reported success with vegetable oil esters in diesel engines including Quick and Woodmore (1984); Hawkins et al. (1983); Wagner et al. (1984); Chancellor and Raubach (1985); Geyer et al. (1984); Pischinger et al. (1982b) and Einfalt and Goering (1985). In most cases engine deposits were reduced to what could be characterized as normal. Wagner et al. (1984) reported that deposits from the ethyl ester were comparable in amount, but slightly different in color and texture when compared to diesel. Methyl and butyl esters showed greater amounts of deposits in the top ring groove of the piston. All researchers report that engine wear was low, fuel consumption was increased but thermal efficiencies and power were nearly identical. The conclusion is that in an emergency the esters could be produced to operate direct injection engines as a complete replacement for diesel.

Pischinger et al. (1982b) found excessive lubricating oil dilution when methyl ester of soybean oil was used to fuel direct injection engines. In indirect engines they found it difficult to identify the fuel by driveability, performance, engine noise or cold starting. Smoke levels were lower and fuel consumption 5 to 6% higher.

Fuls et al. (1984) report on the compatibility of neat sunflower oil and the ester of sunflower oil with the various materials with which they may come into contact in an engine. They report a general tendency to harden all of the plastics and a subsequent change in their tensile strength. High density polyethylene and polypropylene were less affected than the others. Most rubbers were also affected. They suggested Viton-A as the most suitable construction rubber. Experience with tractor operation reveals a serious hostility of the ester toward paint attacking it like a paint stripper. Any tendency to metal corrosion is very low. They conclude that the introduction of esters as a fuel will necessitate the replacement of some fuel lines with a more compatible material. The adhesives in some fuel filters are also attacked by the esters and manufacturers should be consulted before they are used. Pischinger et al. (1982b) found no problems of compatibility of methyl ester of soybean oil with the materials used in the Volkswagen fuel system.

Engler et al. (1983) report that tests with partially esterified cottonseed and sunflower oils (ethyl esters) showed no improvement in performance or amount of engine fouling over unmodified oils. Only completely esterified fuels showed significantly better results than unmodified oils. These results suggest that molecular structure and reactivity oif the fuel are more important than viscosity as factors in the formation of carbon deposits.

The production of esters as a fuel in small on-farm plants raises understandable reservations. Quick and Woodmore (1984) conclude that, "Vegetable oil methyl esters can be produced on a small scale, provided that individuals have an understanding of the chemistry involved and are capable of handling hazardous materials. Maintaining fuel standard is not so easy. Contamination with catalyst is a constant risk and the corrosive effect of catalysts such as sodium hydroxide on engine components can be serious." Additional cost of transesterification is also a problem. Quick and Woodmore (1984) report 60 cents/L for vegetable oil fuels and \$1.25/L for the esters. Kaufman (1985) reported on the economics of five plants for producing methyl esters ranging in size from 36 to 360 kL/day. He states that, "For the two smaller plants transesterification costs of 8.5 and 2.4 cents/L resulted. Plant size three had transesterification cost equal to the market value of the glycercol produced . . ." The two larger plants of 270 and 360 kL/cents/L day generated glycerol with a market value of 1.1 and 1.6 cents/L more than the cost of processing. Having a suitable glycerol market is obviously very important in determining the ultimate cost of transesterified fuel.

Microemulsions

Microemulsions of vegetable oils and lower alcohols with octanol surfactant have several advantages as alternate fuels for diesel engines compared with pure vegetable oils (Schwab, 1984). The microemulsions are reportedly stable at temperatures at low as -10°C when the water content does not exceed one percent. The viscosity of the vegetable oil is reduced to improve combustion and reduce gumming with alcohol which is dispersed in the oil as a microemulsion by means of a single, noncorrosive additive. Goering and Fry (1984) reported on 200 h EMA test evaluations with a mixture of diesel and soybean oil in a microemulsion. They found the hybrid produced less wear than diesel fuel but greater deposits of carbon and lacquer on the injector tips, intake valves and tops of cylinder liners. Engine performance was degraded ca 5% at the conclusion of the test.

Goering (1984) compared four experimental fuels in a 200 h EMA test cycle. All were categorized as passing but all produced heavier carbon and lacquer deposits on the pistons than No. 2 diesel, all produced carbon trumpets around the orifices of the injection nozzles and all produced heavier carbon deposits on the intake valve tulips and in the intake valve ports than did diesel fuel. He concludes that, "Any of the four fuels could be blended on the farm and, despite their above-mentioned limitations, a farmer might reasonably choose to use one of them to keep his equipment moving through a petroleum emergency; if operations on the experimental fuel were extended, an overhaul would be necessary to restore the engine to good condition."

Thus, the microemulsions greatly reduce vegetable oil viscosity and are an improvement over the neat vegetable oils as far as engine operation is concerned but additional improvement is needed.

ECONOMICS OF VEGETABLE OILS AS FUELS

Perhaps an even bigger factor than the engine deposit problem in slowing the move to use of vegetable oil as a diesel fuel is the economics. Diesel costs less and an emergency or diesel shortage would be required in the United State to provide a practical reason for using vegetable oil as a fuel. The current wholesale price of diesel fuel in 5000 gal lots as reported by a fuel distributor in June 1983 was 22 to 24 cents/L. Soybean oil in 19000 L tank car lots was 38.6 cents/kg or 35 cents/L. The prices of the oils were: sunflower oil 57 cents/kg (52.4 cents/L), cottonseed oil 38.6 cents/kg (35.1 cents/L) and rapeseed at $1.22/kg (1.11 cents/L). Collins et al. (1982) commented that, "The mere availability of such substitutes (plant oils) can have a beneficial influence by holding crude oil prices below a certain level."

In some parts of the world vegetable oil is very close to the price of diesel. For example, Johansson and Nordstrom (1982) report that, "A cubic meter of diesel fuel cost 2142 Sw crowns May 10, 1982. The corresponding price of a cubic meter of crude lobra oil (rapeseed oil) was some 2465 Sw crowns."

Helgeson and Schaffler (1982) report "Sunflower seed has a high oil content and an acre will produce about 60 gallons. Each Btu used to produce the seed and process safflower oil will return about 5.78 Btu. The price relationship per Btu of diesel to sunflower oil was 1:4.0 in 1979. This ratio declined to 1:1.8 in 1981."

McIntosh et al. (1982) reporting on the economics of vegetable oils in Idaho stated, "The results indicate that winter rape oil becomes a feasible alternative to diesel when the price of diesel reached $0.84/L in the Latah County model. A diesel price of $0.85/L was required in the Power county model before it became feasible to produce sunflower oil for fuel."

Kaufman (1984) reported that the average energy return ratios for producing crude sunflower oil as an agricultural diesel fuel were estimated at 2.26 and 3.44 for double and single-cropped sunflowers respectively. McIntosh et al (1984) reported energy return ratios of 2.7 and 2.6 for sunflower and 2.3 and 2.2 for safflower under two dryland Idaho conditions. Irrigated sunflower achieved returns of 2.1 and 1.8. Winter rape produced on dryland farms in northern Idaho had a return ratio of 4.2. Both of these estimates include all of the inputs from growing the crop until it is utilized in the engine.

POTENTIAL PRODUCTION OF VEGETABLE OIL IN COMPARISON TO DIESEL FUEL USE

In 1978, U.S. diesel consumption in agriculture was 3.3 billion gallons which would require 3.6 billion gallons of vegetable oil to replace it on an equal energy basis. Ten to 15% of total U.S. cropland would be required to produce the needed vegetable oil. In 1981, 19% of the U.S. cropland was planted to vegetable oil crops. Currently the U.S. is the largest oilseed producing nation (35% of the world production in 1980-81). Oilseed commodity and product exports were worth 8.9 billion in 1979, 25.6% of the total U.S. agricultural exports, Dunn and Schneeberger (1982). U.S. oilseed production is approximately as shown in Table 4.

TABLE 4. U.S. OILSEED PRODUCTION

Crop	Harvested hectares	Percent oil	Liters oil	Liters per ha	% of U.S. cropland
	(000)		(000)		
Soybean	26,987	18	10,780,501	402	14.70
Sunflower	1,414	40	809,896	571	0.80
Cottonseed	5,592	17	631,145	112	3.10
Peanuts	602	31	601,823	992	0.30

U.S. diesel consumption in agriculture 12,521,000,000 L
Vegetable oil equivalent 13,484,000,000 L

TABLE 5. SUNFLOWER LAND AREA (MILLIONS OF HECTARES) REQUIRED FOR DIESEL FUEL SUBSTITUTION AND PERCENT OF TOTAL U.S. CROPLAND

	10%	25%	50%	100%
Millions of hectares	2.46	6.15	12.3	24.6
% of total cropland	1.3	3.4	6.7	13.4

Bjornstad et al. (1982) report that 25% of the diesel demand could be met with 28% of the soybean crop. Meeting all agricultural diesel demands in 1990 would require all of the soybean crop plus an additional 14 percent which would take 77 % of the projected 1990 sunflower crop, see Table 5.

A highly controversial area of interest is the possibility of allowing production of energy crops on land not currently in production because of government programs. In 1984 the ASCS reported that 12.3 million ha were in the acreage conservation reserve. The PIK program of 1983 may have been a more valid indicator of excess land area in production than is the current acreage in conserving use only. The following is based on the 1983 program. In 1983, according to ASCS figures, 30,089,123 ha were devoted to PIK or conserving use. Some have argued that land which can grow food should not be used for energy production. This 30 million hectares was essentially idle land and could easily be used to grow energy. Johnson and Swenson (1983) found tht if government payments were diverted to a sunflower-for-fuel option in North Dakota, for a producer growing 1800 kg/ha, a 24.3 cents/L subsidy would be available for the 304 L of sunflower oil produced, which is enough to make sunflower oil less expensive than diesel.

Table 6 shows the impact that land in government programs could have on agricultural diesel use.

PRIORITIES FOR ADDITIONAL RESEARCH

Definite strides have been made in the technology to

TABLE 6. 1983 PIK AND CONSERVING USE LAND AREA POTENTIAL FOR VEGETABLE OIL PRODUCTION CONSIDERING TWO DIFFERENT LEVELS OF OIL YIELDS

Total hectares - 30,089,122		
	Oil yield 375 L/ha	Oil yield 560 L/ha
Oil prod. -	11.3 billion L	17.0 billion L
% of agriculture diesel use	83%	125%

use vegetable oils as a replacement for diesel fuel in the past six years since the energy crisis stimulated new interest in alternate fuels. Problem areas have been identified, some solutions have been found, but much more remains to be done. The encouraging thing is that vegetable oils do have excellent potential as a replacement for diesel fuel, especially in an emergency petroleum shortage. However, undiluted vegetable oils, especially the highly unsaturated types, can cause rapid engine deterioration due to polymerization and carbon deposits. The high viscosity of the oils cause poor atomization and injector spray patterns. Research has shown that these problems can be largely overcome through blends, microemulsions or transesterification. Much remains to be learned about each of these before general certification as a fuel could be achieved. Vegetable oils could be used as a substitue for diesel fuel in an emergency; however, reduced engine life may occur. Nevertheless, Caterpillar Brazil and Deutz in South Africa have announced qualifed warranties on their indirect injection diesel engines when operated on certain oils in those countries only.

The following list of research priorities is summarized from information received from those most closely allied with the vegetable oil fuel technology. Items are not listed in a particular order of priority. The current status of vegetable oil as a replacement for diesel fuel is such that the following are recommended for further study:

1. Encourage those individuals who make the decisions on where research funding should be allocated that development of vegetable oil technology should be continued pending a need for implementation. The fuel problem has not gone away; it is only deferred at the present time.

2. Search for new oil crops for the various production areas of the world; include consideration of "non-traditional" oil bearing crops such as the Chinese tallow tree and the buffalo gourd.

3. Use biotechnology to develop new plant cultivars especially tailored for high oil production and best fuel quality.

4. Optimize crop production practices for vegetable oil crops best adapted for each area of the country.

5. Conduct research aimed toward understanding and reducing coking and carbon formation in diesel engines.

6. Completely describe the specifications for a diesel fuel extender; particularly, chemical characterization. Also more complete engine performance mapping of all oils is needed.

7. Studies on methods to overcome the coking problem with neat vegetable oils as fuels are needed.

8. Investigate injector modifications to improve fuel atomization, combustion and reduced coking.

9. Improved lubricating oils for use with vegetable oil fuels should be developed.

10. Long term engine tests with vegetable oil blends, particularly in the smaller percentages such as 5 and 10 percent vegetable oil, are needed to determine if a small amount of vegetable oil can be used successfully as a general diesel extender.

11. Long-term engine tests on several of the vegetable oil esters should be perfomed. Oil change requirements and general maintenance procedures to follow when using ester fuels must be determined.

12. Tests to determine the effect of unsaturation level in esterified fuels should be a research priority.

13. Research to find a solution to the problem of high cloud point and solidification temperatures of the ester fuels should be undertaken.

14. Additional studies are necessary with ester fuels to determine solutions to their tendency to cause injector nozzle needle sticking and dilution of crankcase oil at light engine loads; also, to determine additional problems which may become evident with more and longer engine tests.

15. Studies on low temperature handling characteristics of vegetable oils are essential to determine year around operation.

16. On-farm field testing of vegetable oil blends, microemulsions and transesterified oil must be extensively carried out, under a variety of conditions, before general certification as a fuel is possible.

17. Improved expression of vegetable oils is needed as is research into optimum oil extraction methods for use in small and medium sized plants.

18. Research into technical and economic feasibility for producing ester fuels on the farm and at the local cooperative level is necessary before these fuels oils could be available.

19. Study catalyst stripping techniques to eliminate water washing during transesterification and to assure complete catalyst removal to eliminate possible engine corrosion problems.

20. Research is needed to improve compatibility of the esters with paint.

21. Determine safe methods for storing the ester fuels that will not alter their fuel properties.

22. Study production strategies to improve the economics of using vegetable oils as fuels.

23. Study alternate uses for vegetable oil production by-products including use of the meal as feed, fertilizer and in direct combustion and use of the glycerol from the transestification process.

24. Determine the qualities of vegetable oil feedstocks that could be available and the corresponding prices if a petroleum emergency occurred.

25. Design engines tailored specifically to optimize the use of vegetable oil blends as fuel.

26. Study the use of vegetable oils in gas turbine engines.

27. Research to develop improved microemulsions which could be blended on the farm in time of emergency shows promise and should be continued.

28. Investigations with fuels produced through pyrolysis of the triglycerides is just beginning and should be encouraged.

29. Further research to find diesel fuel substitutes which can be blended from other renewable feedstocks but which would produce fewer undesirable deposits and maintenance problems in diesel engines could lead to additional fuel strategies.

30. A final research priority should be to summarize all data and conclusion from recent studies in order to define the current state of vegetable oil as a diesel fuel technology so that this work will be carefully documented and will not be repeated at some later energy crisis. Since many research programs have been terminated or greatly reduced in scope, funds are not available even to prepare and present final papers. A special international

vegetable oil conference with funds specifically for this purpose would be of inestimable value.

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APPENDIX 1. TYPICAL OIL SEED YIELDS*

Common name	Scientific name	Seed or oil yield, kg/ha	% oil
Ajipo	Pachyrhizus tuberosus (Lam.) Spreng.	600 sd	
Alfalfa seed	Medicago sativa	800 sd	8-11
Almond	Prunus dulcis (Mill.) D.A. Webb	3000 sd	50-55
Ambrette	Ablemoschus moschatus Medik	836-1693 sd	
Bean, adzuki	Vigna angularis (Willd.) Ohwi and Ohashi	1100 sd	
Bean, lima	Phaseolus lunatus L.	2500 sd	
Bean, mung	Vigna radiata (L.) Wilczek var. radiata	1100 sd	
Bean, rice	Vigna umbellata (Thunb.) Ohwi and Ohashi	200 sd	
Bean, scarlet runner	Phaseolus coccineus L.	1700 sd	
Bean, tepary	Phaseolus acutifolius A. Gray	1700 sd	
Cacao	Theobroma cacao L.	3300 sd	35-50
Calophyllum	Calophyllum inophyllum		50-73
Cashew	Anacardium occidentale L.	1000 sd	
Castorbean	Ricinus communis L.	5000 sd	35-55
Chickpea	Cier arietinum L.	2000 sd	
Coconut	Cocos nucifera L.	1000 copra	62.5
Colocynth	Citrullus colocynthis (L.) Schrad.	6700 sd	47
Cotton	Gossypium hirsutum L.	900 sd	16
Crambe	Crambe abyssinica Hochst. ex R.E. Fries	5000 sd	25-33
Croton, purging	Croton tiglium L.	900 sd	50-55
Crownvetch	Coronilla varia L.	500 sd	
Elderberry	Sambucus canadensis		22-28
Fenugreek	Trigonella foenum-graecum L.	3000 sd	
Flax	Linum usitatissimum	650 sd	34
Gourd, buffalo	Cucurbita, foetidissima HBK	3000 sd	24-34
Grape seed oil	Vitis vinifera		6-21
Guar	Cyamopsis tetragonoloba (L.) Taub.	2000 sd	
Hemp	Cannabis sativa L.	1500 sd	25-30
Jicama	Pachyrhizus erosus (L.) Urb.	600 sd	
Jojoba	Simmondsia Chinensis (Link) C. Schneid	2250 sd	43-56
Kapok	Ceiba pentandra		20-25
Lentil	Lens culinaris Medik.	1700 sd	
Lesquerella	Lesquerella spp.	1121 sd	11-39
Lupine, white	Lupinus albus L.	1000 sd	
Marihuana	Cannabis sativa L.	1500 sd	
Meadowfoam, Baker's	Limnanthes bakeri J.T. Howell	400 sd	24-30
Meadowfoam, Douglas's	Limnanthes douglasii R.Br.	1900 sd	24-30
Mu-oil tree	Aleurites montana (Lour.) Wils.	5500 oil	
Mustard, black	Brassica nigra (L.) Koch	1100 sd	30-35
Mustard, greens	Brassica juncea (L.) Czern	1166 sd	30-38
Mustard, white	Sinapis alba L.	8000 sd	25-30
Niger seed	Guizotia abyssinica (L.f.) Cass	600 sd	25-35
Nut, macadamia	Macadamia spp.	4000 sd	15-20 of nut
Oilvine, Zanzibar	Telfairia pedata (Sm. ex Sims) Hook.	2000 sd	35
Palm, African Oil	Elaeis guineensis Jacq.	2200 oil	55 of kernel
Pea, cow	Vigna unguiculata (L.) Walp.	2500 sd	
Pea, garden	Pisum sativum L.	1800 sd	
Peanut	Arachis hypogaea L.	5000 sd	35-55
Perilla	Perilla frutescens (L.) Britt.	1500 sd	35-45
Poppy, opium	Papaver somniferum L.	900 sd	45-50
Rape	Brassica napus L.	3000 sd	40-45
Rice bran	Oryza sativa	800 sd	15-20
Safflower	Carthamus tinctorius L.	4500 sd	35-45
Sesame	Sesamum indicum L.	1000 sd	45-50
Soybean	Glycine max (L.) Merr	3100 sd	13-25
Stokes aster	Stokesia laevis (Hill) Green	1121 sd	27-44
Style, Townsville	Stylosanthes humilis H.B.K.	1200 sd	
Sunflower	Helianthus annuus L.	3700 sd	40-50
Tallow tree, Chinese	Sapium sebiferum (L.) Roxb.	14000 sd	19
Trefoil, birdsfoot	Lotus corniculatus L.	600 sd	
Tung-oil Tree	Aleurites fordii Hemsl.		
Tsubaki	Camellia japonica		66
Turnip	Brassica rapa L.	1000 sd	
Velvetbean	Mucuna deeringiana (Bort) Merr.	2000 sd	
Walnut, black	Juglans nigra L.	7500 sd	60
Walnut, Persian	Juglans regia L.	7500 sd	63-67

*Adapted from Duke and Bagby (1982) and Jamieson (1943).