Appendix B

Selected Industrial Uses for Traditional Crops

Diesel Fuel From Vegetable Oils

Crop: Sunflowers, soybeans, potential new crops such as rapeseed

Major coproducts: Oil, meal, and potentially glycerol

Major uses: The oil can be used as diesel fuel, and the meal as livestock feed. Glycerol is a widely used chemical.

Replacement: Diesel fuel derived from petroleum products. The United States uses approximately 40 billion gallons of diesel fuel yearly, with about 3 billion gallons used for agricultural purposes.

Technical considerations: Chemical and physical composition of the oil determines fuel characteristics. In general, highly unsaturated oils break down faster than saturated oils, but increased saturation leads to solidification at near-room temperatures. Unsaturation is desirable for maintaining liquidity at low temperatures, but undesirable for stability. Ignition quality (cetane number) generally is lower for vegetable oils than for diesel fuels, and vegetable oils have lower heat of combustion. The most serious problem related to using vegetable oils as diesel fuel is their viscosity. Viscosity is critically dependent on temperature, and the viscosity of vegetable oils is more affected by temperature than the viscosity of diesel fuels. The pour points of vegetable oils are also higher than those of diesel fuels, which could create problems in colder climates.

Vegetable oils can be used straight or blended with diesel fuel. Short-term testing of oilseed fuels indicated that these fuels were roughly equivalent to diesel fuel. Fuel consumption was higher because vegetable oils have a lower heat of combustion than diesel fuel. Longer-term tests have had problems of deposit buildup in the combustion chamber and injector nozzle (due to the poor thermal stability of vegetable oils) and piston ring sticking and engine failure (due to decreased fuel atomization and combustion efficiency), particularly in direct-injection diesel engines, the most common type of diesel engine used in the United States. Problems have not been as serious in indirect-injection diesel engines.

Alternatively, vegetable oils can be converted to monoesters, by reacting the oil with alcohol in the presence of a catalyst. Three monoester molecules and a glycerol molecule are obtained from each triglyceride (the process is similar to deriving fatty acids from oils to be used for plastics, soaps, lubricants, etc.). The resulting ester fuels have viscosities similar to those of diesel fuels and also tend to vaporize in a manner more similar to diesel fuel. Short-term tests using methyl esters of rapeseed oil in direct-injection diesel engines appeared not to result in the carbon deposit buildup that occurs with the blends or straight vegetable oils. Using ethyl esters of various degrees of saturation in short-term tests indicated that the unsaturated esters resulted in more coking than the saturated esters. Longer term testing of monoesters derived from soybean oil results in a polymerization and varnish buildup in the cylinder walls. Methyl esters tend to crystallize at 4 to 5° C, requiring storage and transport in heated vessels. Ethyl esters have better low-temperature properties but have higher conversion costs due to water contamination problems.

The land needed to supply enough oil for agricultural diesel use alone could be a constraint. Oilseeds that are high yielding and contain a high percent of oil are preferable. Potential candidates are peanuts (40 to 45 percent oil), cottonseed (18 to 20 percent oil), safflower (30 to 35 percent oil), rapeseed (40 to 45 percent oil), sunflower (35 to 45 percent oil), and soybeans (18 to 20 percent oil). Peanuts and cottonseed are unlikely candidates for economic reasons. Safflower and rapeseed currently are grown only in small quantities; production would need to be greatly expanded. Soybeans and sunflowers are the likely candidates. Average U.S. sunflower yields are about 600 pounds oil per acre, while soybeans yield about 400 pounds per acre. For sunflowers to supplant soybeans as a major oil source, expansion of production is necessary.

Economic considerations: The value of soybeans and sunflowers depends on the value of both the oil and the protein meal produced. The ratio of oil to meal produced, and the percent of the value of the oilseed accounted for by the oil, will in large part determine the supply response of the oilseed to an increased demand for the oil and the economic competitiveness of using that oil for fuel. Soybeans may be self-limiting because more than 60 percent of the value is for the meal. Supplying more soybean oil also results in a greater supply of meal, which decreases the price of the meal. Production will occur up to the point where the increases in oil price offset the decreases in meal prices, unless new markets for meal can be found. These impacts may be more significant for on-farm rather than off-farm processing.

For sunflowers, it is possible to produce enough oil to replace diesel fuel use without producing excessive meal for on-farm livestock use. Unfortunately, sunflower meal is low in lysine and cannot fully supply the protein requirements of livestock particularly pork and poultry. Farmers would still need to purchase higher-lysine-protein meal, such as soybean meal, or amino acid supplements. This to some extent decreases the attractiveness of on-farm extraction of sunflower seeds. Whether a combination of sunflowers and soybeans is possible is not clear.

The cost of converting sunflower oil to fuel-grade methyl esters is about $1.00 per gallon. A 25 gallon/hour plant can produce fuel-grade sunflower oil-methyl ester for about $3.25 per gallon, a price about three times higher than diesel fuel.

Social considerations: On-farm extraction of oils potentially could have negative impacts on employment, particularly in the oil processing and transportation industries. Increased centralized processing could potentially increase employment in these industries. Total replacement of agricultural uses of diesel fuel would result in small petroleum savings because this market represents about 1 percent of total petroleum use. Conversion of soybeans to fuel uses will decrease agricultural exports unless increased markets for the meal can be found. Edible-vegetable-oil prices will likely increase. Vegetable oils are expected to burn cleaner and cause less air pollution than diesel fuels.

SOURCES: 15,19,24,34

Soybean Uses

Crop: Soybeans

Major coproducts: Oil, flour, and protein

Major uses: The flour is used to make adhesives, mainly for plywood. The oil is used in alkyd paints, as a plasticizer and stabilizer in vinyl plastics, as an antifoamant in fermentation processes, as a carrier for printing ink, as a carrier for agricultural chemicals, and to control grain dust in elevators. The protein is used to make adhesives that bind pigment to paper in the coating process. Historic uses, which are no longer available, include the use of soybean fiber to make blankets, upholstery, and other textiles (marketed as Azlon), and the oil combined with lime and sprayed through an aerator nozzle for extinguishing fires.

Replacement: Petroleum-derived products

Technical considerations: Historically, soybeans have been used for all of the above uses, but have been replaced by petroleum products primarily for economic reasons. Some of the technical problems include a lack of water resistance for the flour adhesives and poor durability, peeling, and scaling of paints, which limits them to indoor use. Today, about 7,000 tons of soy flour and 8,000 tons of soy protein are used to make adhesives. Each year, approximately 120 million pounds of oil are used in the plastics and resins industry and about 40 million pounds of oil are used in the paint and varnish industry.

Soy inks were developed by the American Newspaper Publishers Association in 1985. Soy inks are clear so the pigment shows better and they do not smudge as much as petroleum inks. Newspaper publishers use about 500 million pounds of ink each year which would require approximately 350 million pounds of oil. Approximately one-third of the U.S. newspapers are using soy-based inks for color printing.

Soybean oil used in small volumes (0.02 percent by weight) can be used to suppress dust in grain elevators (up to 99 percent). When compared to untreated grains, use of soybean oil as a dust suppressant does not appear to affect odor, grade, drying characteristics, mold growth, or milling and baking qualities, and there may be some improvement in insect control.

Economic considerations: Food and livestock-feed uses keep the price of soybeans high enough that use for industrial purposes is often precluded. The situation could change if the price of petroleum increases.

Soy oil ink cost *50* to 60 percent more than petroleum-based ink, because more steps are involved in its manufacture (i.e., it costs about 90 cents per pound compared to petroleum-based inks, which cost about 60 cents per pound). For color inks, however, the cost of the color pigments is the major cost, and soy inks have gained in this usage. Also, more papers can be printed per pound of soy ink than convential ink because the color pigments blend better with soy oil than pretroleum-based oil and thus, can be applied in a thinner layer.

SOURCES: 3,5,16,20,28,34,38

Road De-icers

Crop: Corn primarily, but potentially other starch or lignocellulose sources

Major **coproducts:** Starch, oil, and protein feeds

Major uses: Road deicer

Replacement: Road salt

Technical considerations: Calcium magnesium acetate (CMA) is made by reacting acetic acid with dolomitic limestone. The acetic acid can be obtained by fermentation of corn, however, at present, no large-scale plants exist. The Chevron Co. has marketed CMA. Determination of the optimal bacterial strain for acetic acid production is needed. Approximately 60 bushels of corn are needed to make 1 ton of CMA.

Economic considerations: Acetic acid can be obtained from corn fermentation (or starch or cellulose from other sources) or petroleum sources. Estimates are that using corn priced at $2.80 per bushel would result in production costs of 18 to 19 cents per pound of CMA. This is 7 to 8 times the cost of road salt. CMA bound to sand to increase traction costs about 10 times more than road salt. Utilizing ground corn cobs as the feed stock instead of corn kernels might lower the cost to 12 to 14 cents per pound of CMA. There does not appear to be a significant difference in costs of production utilizing anaerobic (without oxygen) or aerobic bacterial fermentation. It is estimated that an economical size plant would have a capacity of 500 tons/day and a yearly capacity of about 150,000 tons. This size plant would utilize 9 million bushels of corn per year, with 45,000 tons of distillers dried grain as a byproduct. The U.S. uses about 10 million tons of salt per year. Capturing 10 percent of this market would utilize 60 million bushels of corn.

Social considerations: Significant expanded production could increase corn prices, and create dried distillers grains that would compete with soybean meal in the high-protein livestock feed market. A major attraction of CMA is that it has less negative environmental impacts than salt. It is less harmful to animals and the soil than salt, and is 10 times less corrosive. Estimated costs of vehicle corrosion and damage to roads and bridges caused by salt are about $5 billion yearly.

SOURCES: 12,21

Coal Desulfurization

Crop: Corn primarily, but potentially other starch or cellulose sources

Major coproducts: Ethanol, oil, and protein feeds

Major **uses: Coal** desulfurization

Replacement: Scrubbers and other sulfur removers

Technical considerations: Carbon monoxide and either ethanol or methanol can be used to remove sulfur from coal. One ton of processed coal produces 1/2 barrel of crude oil, 25 pounds of carbonyl sulfide (used in agrichemicals and pharmaceuticals), 35 pounds of hydrogen sulfide (used in pharmaceuticals), 8.3 gallons of acetaldehyde (used to make either acetic acid or acetone), and iron sulfide, which can be burned for heat. Currently, testing at a 1 to 10 pound/hour scale is occurring. The next stage will be to test at the 30 to 100 pound/hour scale and if the procedure continues to look promising, construction of a pilot plant to process 2,000 pound/hour will begin. Funding will be sought from the Clean Coal Technology Program (Department of Energy) for plant construction.

Economic considerations: A 1986 study by the Center for Research on Sulfur in coal estimated the cost of the carbon monoxide ethanol method to be $134 per ton of coal ($5.02 per million Btu). In 1986, the cost of low-sulfur coal was $49.70 per ton. Improvements in technology are needed to significantly lower the cost. The ethanol used could potentially be derived from corn. About 8 gallons of ethanol are required to process one ton of coal (about 3 bushels of corn).

Social considerations: The United States has large deposits of coal, which potentially could be used in place of petroleum. However, much of the coal contains sulfur, which can lead to acid rain when burned. Removing the sulfur is expensive. An economical method to remove sulfur would allow coal to be used in place of petroleum. However, technical difficulties and the fact that ethanol derived from corn fermentation varies greatly in price because of variability in corn and byproduct prices will make widespread use of this technology difficult at the current time. There is also some concern that increased burning of coal will increase carbon dioxide levels.

Research conducted: A joint venture is being conducted by Southern Illinois University-Carbondale (SIU-C), the Illinois State Geological Survey (ISGS), the Univeristy of North Dakota Energy and Environmental Research Center, Ohio University, and Eastern Illinois University. Funding is provided by the Illinois and Ohio Corn Marketing Boards, ISGS, SIU-C, the Illinois Department of Energy and Natural Resources, and the U.S. Department of Energy.

SOURCES: 21,45

Super Absorbants

Crop: Corn

Major coproducts: Cornstarch which has been modified to absorb up to 1,000 times its weight in moisture, oil, and protein feeds.

Major uses: These modified starches are currently used in disposable diapers (about 200 million pounds/year) and as a burn treatment. They are also being used in fuel filters to remove water. They could also be used as a seed coating to increase germination, as an agricultural chemical delivery system, and as a soil conditioner.

Technical considerations: As a soil conditioner, corn starch polymers bind soil particles into stable aggregates, which results in better aeration and increased water penetration and retention. There are two types of polymers used: 1) hydrogels and 2) water-soluble linear polymers. Hydrogels are polymers crosslinked to adjacent molecules so that the structure is insoluble in water. They act like a sponge, absorbing 50 to 400 times their weight in water and delivering 40 to 95 percent of the water to plant roots. They increase the water-holding capacity of sandy soils and reduce frequency of irrigation. Soil moisture supply is more constant. Water-soluble linear polymers are large chains of repeating units. They do not hold water. Rather, they bind soil particles together to form lattices and as such maintain soil in a loose and friable state. The bound soil particles are stable in water. There is less evaporative loss because the top layer of polymer-treated soils acts like a mulch. Besides cornstarch, guar polysaccharides and lignin can be used to make the polymers.

Modified corn starch can be used as an encapsulating agent for active ingredients such as herbicides. The advantages of encapsulation are: 1) extension of activity, 2) reduction of evaporative and degradative loss, 3) reduction of leaching, and 4) decrease in the dermal toxicity of the active agent. Encapsulation involves dispersing the starch in aqueous alkali followed by crosslinking reactions after the active agent has been interspersed. Corn starch can be used as an entrapment agent for both solid and liquid active agents. The efficiency of encapsulation and rate of release of active agents depends on starch type, temperature and concentration of starch during gelatinization, amount of active agent incorporated, and method of drying. Preliminary data indicates that herbicides encapsulated in corn starch are less mobile in soil and could potentially reduce the possibilities of groundwater pollution. One technical goal is the elimination of chemicals used to form the matrix because these chemicals prohibit using many encapsulated products for food or livestock feed.

Economic considerations: Byproducts of corn grown for starch compete with soybeans in the livestock feed market. Price for the starch-based products will fluctuate with the price of corn and the value of these feed byproducts.

Social considerations: There is some potential to decrease groundwater contamination by using encapsulated pesticides. Livestock feed byproducts will compete with soybeans.

Research conducted: Northern Regional Research Center in Peoria, Ill.

SOURCES: 6,18,41,43

Ethanol

Crop: Corn primarily, but potentially other starch or lignocellulose sources

Major coproducts: Two production methods are utilized: dry-mill and wet-mill corn processing. In dry-mill processing, the corn is ground, slurried with water, and cooked. Enzymes convert the starch to sugar, and yeast ferments the sugars to a beer that contains water, alcohol, and dissolved solids. The solids are dried and sold as dried distillers grain (a livestock feed). The remaining beer is distilled and dehydrated to form anhydrous ethanol, with CO_2 as a byproduct. One bushel of corn produces approximately 2.5 to 2.6 gallons of ethanol and 18 pounds of dried distillers grain.

In wet-mill processing, corn kernels are soaked in water and sulfur dioxide, and the portions of the corn kernel other than the starch are removed. These portions are used to make corn oil, corn gluten feed (20 to 21 percent crude protein) and corn gluten meal (60 percent crude protein), which can be used as high-protein livestock feeds. The almost pure starch that is left is converted to sugar, then fermented and distilled to produce ethanol and CO_2. Because the wet-mill production process is identical to the process used to produce high-fructose corn syrup through the starch phase, the two operations can be combined in the same plant, resulting in a significant production cost saving. One bushel of corn produces 2.5 to 2.6 gallons of ethanol, 2.5 pounds of gluten meal, 12.5 pounds of gluten feed and 1.6 pounds of corn oil. In 1985, approximately 60 percent of the nearly 800 million gallons of ethanol produced came from wet-mill plants.

Major uses: Either as a fuel, a fuel extender, or as an octane enhancer.

Replacement: Gasoline

Technical considerations: Vehicle problems have been encountered with ethanol/gasoline blends. Altering the volatility level is required to prevent warm-weather stalling. First-time use in older cars can result in fuel filter clogging because ethanol is a solvent that dissolves built-up gums and deposits already in the system. Blends might separate in the presence of water. Use is not recommended for vehicles left idle for long periods such as recreational vehicles. Most automobiles have now been adjusted to minimize such problems.

Ethanol production needs to be improved. In the near term, three new technologies show promise: 1) replacement of yeast with *Zymomonous* mobilis bacteria, 2) membrane separation of solubles, and 3) yeast immobilization. Z. mobilis ferments faster than yeast, and tolerates a greater temperature range. It also has a higher selectivity for producing ethanol and gives greater yields. Membrane separation of solids reduces energy requirements by removing as much as 40 percent of the water prior to boiling. Membrane clogging is a problem. Immobilization allows the sugar or starch solution to be passed over the enzymes, bacteria, or yeast. Use of the enzymes and yeast is maximized, and contamination concerns are reduced by eliminating yeast recycling. Immobilization is applicable only to wet-milling because it requires a clarified substrate.

If ethanol production is to be increased significantly, feedstocks other than corn will be needed. Alternatives are high-starch or cellulosic biomass. Potential cellulosic candidates include forage crops (e.g., alfalfa stems or fescue), crop residues (e.g., corn stalks), or municipal wastes (e.g., wood chips or sugar beet pulp). Attempts are being made to identify microorganisms that convert wood hemicellulose into high yields of sugar and alpha cellulose. New processes that increase the efficiency of converting cellulose to sugars are being developed.

Economic considerations: Large plants (annual capacities of 100 to 150 million gallons) are able to capture economies of scale in both the production and marketing of the fuel. Small plants (0.5 to 10 million gallons annually) can be profitable under conditions such as: 1) location in areas of limited local grain production and high transportation costs to major grain markets, 2) joint location with food processing or other industrial facilities where fermentable wastes are produced, or 3) location near a feedlot where byproducts can be fed directly to livestock without drying.

Costs of ethanol production are highly variable because of fluctuating prices for corn and byproducts. Feedstock costs (the net of the price paid for the corn and the credit received for selling the byproducts) have ranged from $0.10 to $0.79 per gallon of ethanol in recent years. Other cash operating expenses, such as labor, energy, and administration, have ranged from $0.35 to $0.65 per gallon of ethanol depending on the size of the plant. Energy costs average about 36 percent of the cash operating expenses. Investment costs to build an ethanol plant range from $1.00 to $2.50 per gallon of installed capacity. Construction of a new dry-mill plant with 40-million-gallon annual capacity is about $2.00 to $2.50 per gallon capacity. Adding ethanol production capacity to a wet mill already producing high-fructose corn syrup costs about $1.00 to $1.50 per gallon capacity. It is estimated that the capital charge per gallon of ethanol produced is $0.19 to $0.48. For a stand alone (ethanol production only) plant, total production costs (feedstock costs, cash operating costs, and capital costs) have ranged from a low of $0.75 per gallon (in a year with exceptionally high byproduct prices) to an average of $1.40 to $1.50 per gallon. Ethanol production at high-fructose corn syrup production plants can reduce production costs by as much as $0.20 per gallon.

Currently, gasoline/ethanol blends (required minimum of 10 percent ethanol) are exempted from 6 of the 9 cents Federal excise tax on gasoline, which is equivalent to a 60 cent per gallon subsidy for ethanol. Additionally, 28 states offer state fuel tax exemptions or producer subsidies which average 20 to 30 cents/gallon. Using corn priced at $2.00 per bushel, and maintaining Federal subsidies, ethanol is competitive with petroleum at $22 to $24 per barrel in plants using the average technology available, at $20 per barrel in new state-of-the-art wet-processing milks, and at $13 per barrel at extensions of high-fructose corn syrup mills. Removal of the Federal excise tax exemption and corn prices of $2.50 per bushel implies that petroleum prices of about $40 per barrel are needed for ethanol to be price competitive with gasoline.

Ethanol yields from cellulosic biomass have been increased from about 40 gallon/ton of biomass to 60 gallon/ton. Approximate cost is $1.50 to $2.00 per gallon. Wood used for energy is both lower valued and more expensive to harvest because harvesting operations are geared to removing large logs. Improvements in harvesting would lower costs. Collecting agricultural residues is also expensive. Municipal wastes may offer the best feedstock source. Currently, ethanol production from cellulose is more expensive than corn but could be competitive with corn at corn prices in the $3.50 to $4.00 per bushel range.

Methyl tertiary butyl ether (MTBE) competes with ethanol as an octane enhancer. Currently, MTBE sells for about $0.70 per gallon. Ethanol sells for $1.20 per gallon, but because of the 60 cents per gallon Federal subsidy, ethanol is less expensive than MTBE. MTBE production costs are sensitive to the price of methanol and butanes. Most production expansion is likely to occur in oil-producing regions, which can take advantage of low-cost methanol supplies. Refiners who have already committed to internal production of MTBE are likely to continue using it rather than ethanol. Use of ethanol is further discouraged by the need to physically separate it from gasoline to prevent phase separation. Independent fuel distributors who do not use pipelines for fuel transport and who must purchase high-octane blending agents are likely to be the primary customers of ethanol for octane enhancement. Passage of the Clean Air Act which mandates use of oxygenates to reduce pollution in some cities may enhance the position of ethanol relative to MTBE.

Increased production of ethanol affects the corn market, the oilseed market, and potentially the livestock and other grains markets. Ethanol production raises corn prices and decreases the price of soybean meal because of the high quantity of gluten feeds produced as a byproduct of ethanol production. Falling soybean prices and rising corn prices cause a shift of acreage from soybean to corn production, particularly in the Corn Belt. It is unlikely that livestock production will be significantly affected unless ethanol production exceeds 3 billion gallons annually because increased corn prices would be offset by decreased protein-supplement prices. Above 3 billion gallons, lower byproduct-feed prices would possibly result in increased beef production. Large-scale expansion of ethanol production is unlikely unless exemption from federal excise taxes are guaranteed at least through the year 2000 (the exemption is due to expire in September 1993). Without the continuation of the exemption, ethanol production is not expected to exceed 1.1 billion gallons. With the exemption continued through 2000, ethanol production could expand to a level of 2.7 billion gallons by 1995, which would trigger higher corn prices and use an additional 800 million bushels of corn. Increased production of protein byproducts would require finding export markets if the byproducts are to maintain their value. Passage of the Clean Air Act is expected to create additional incentives for the use and expanded production of ethanol.

Social considerations: Environmental concerns have renewed interest in alternative fuels. The Clean Air Act mandates that states implement plans to control emissions when concentrations of lead, sulfur dioxide, nitrogen dioxide, ozone, carbon monoxide, and particulate matter exceed standards. Many of these pollutants are found in motor vehicle emissions. Because ethanol contains oxygen, addition of ethanol to gasoline increases the air-to-fuel ratio, and carbon monoxide and hydrocarbon emissions are decreased. Nitrogen oxide emission levels increase. Addition of ethanol to gasoline increases fuel volatility and thus increases the emission levels of volatile organic compounds, which in the presence of sunlight form ozone. MTBE also reduces carbon monoxide without increasing fuel volatility.

Significant changes in aggregate farm income for grain producers as a result of market price changes is unlikely to occur because of the impact of the commodity support programs. For corn producers, ethanol production would need to increase to the 3 to 4 billion gallon range by 1995 to exceed corn target prices if they remain at current levels. Large increases in ethanol production would benefit corn producers, and possibly other grain producers, but harm soybean producers. Because of differences in regional production patterns, there could be significant interregional impacts. The Corn Belt could gain, and the Delta Region and Southeast could lose.

A U.S. Department of Agriculture Economic Research Service study found that if commodity programs in the 1990 farm bill remain similar to those in the 1985 Food Security Act and the Federal excise tax exemption is extended through the year 2000, then expanding ethanol production to the 2.7 billion gallon level would result in Federal commodity program savings exceeding federal ethanol subsidies through *1994.* After that, ethanol subsidies exceed farm program savings. Furthermore, by the year 2000, the cumulative cost of the ethanol subsidies exceeds the cumulative savings of the commodity programs.

Estimates are that production of 3 billion gallons of ethanol would increase direct employment by 3,000 to 9,000 jobs. No estimate was made for indirect employment impacts or for employment that may be lost in other sectors of the economy.

SOURCES: 2,10,12,13,22,36,39,40,46

Degradable Plastics

Crop: Corn primarily, but other starch or cellulose sources are possible

Major products: Starch, oil, and protein feeds

Major uses: Degradable plastics

Replacement: Nondegradable plastics

Technical considerations: First generation degradable plastics are generally of two types; photodegradable and/or biodegradable. Photodegradable plastics degrade in the presence of ultraviolet light and are produced by adding photosensitive agents (e.g., photosensitive transition-metal salts or organometallic compounds) or by forming copolymers with photosynthetic groups (e.g., carbonyl groups). Photodegradable six-pack rings, films, and bags are commercially available.

Biodegradable plastics are designed to degrade in the presence of microorganisms. The most common method used incorporates starch and usually some autooxidants (i.e., compounds that form free radicals that accelerate polymer chain break down) into the plastic. Early products generally contained about 7 percent starch because this was the maximum loading many plastic polymers could handle without processing or equipment changes. Newer methods are using higher starch levels. The U.S. Department of Agriculture has, for instance, developed a method that mixes dry starch or starch derivatives with dry synthetic plastic, water, sodium hydroxide, and urea. Plastics containing as much as 50 percent cornstarch can be made, but durability decreases. Biodegradable plastic bags and agricultural mulches are commercially available.

Another possible approach is the formation of starch (or lignin or cellulose) copolymers with plastics. Radiation or chemicals can be used to generate free radicals (reactive sites) on the starch molecule. These free radical sites are then reacted with a polymerizable monomer (a building block for plastics), which is then polymerized. Alternatively, in place of using free radicals, a third polymer compatible with both the synthetic plastic and the lignin, starch, or cellulose is used. This third polymer links to each of the other two polymers to forma stable bond. The physical properties of these copolymers, particularly water volubility, depend on the nature of the synthetic plastic used. Hydrophilic polymers, such as polyacrylamide, will disperse in water. Hydrophobic polymers, such as polystyrene, will not. This method offers flexibility as to the types of plastics that can be made.

The approaches described above to produce biodegradable plastics all use some combination of biological and petroleum based polymers. Second generation biodegradable plastics are being developed that utilize biological polymers (i.e., starch, cellulose, lactic acid, etc). Under certain conditions, starch can be combined with water to create a compound that is somewhat similar to crystalline polystyrene, and that disintegrates in water. Lactic acid-based biodegradable plastics are being produced from raw materials such as potato and cheese wastes. The bacteria *Alicaligenes* eutrophus can use organic acids and sugar as a feedstock to produce poly(hydroxybutyrate-hydro-xyvalerate) polymers (PHBV) which can be injection molded and made into films with conventional plastic processing equipment. Other bacteria such as *Klebsiella* pneumonia convert glycerol (potentially derived from vegetable oils) into acrolein which can be used to make acrylic plastics.

A major constraint to the acceptance of degradable plastics is the lack of a clear definition of degradability. It is not known under what conditions these plastics degrade and what is contained in the residues left behind. USDA is testing degradability of blended plastics and beginning to develop assays to measure degradability. The special strains of bacteria developed for the assays were able to degrade the starch in the blends within 20 to 30 days. However, after 60 days, the plastic part of the blends was intact. The plastic films used did not visually appear different, but pits where the starch had been were found on electron microscope scans. The plastic films had lost tensile strength and were susceptible to mechanical breakup. For films that will be used as agricultural mulches and then plowed under the ground, this type of degradation might be acceptable. For many other uses, it may not be. Additionally, tests performed in soil showed that the rate of degradation varied substantially among different soil types.

Starch/plastic blends containing less than 30 percent starch degrade slowly. Some studies have shown that a threshold value exists at 59 percent starch loading. Below 59 percent, only 16 percent of the starch particles are accessible to each other; above 59 percent loading, 77 percent of the starch particles are accessible to each other which greatly accelerates degradation. Most commercial degradable starch/plastic blends contain about 6 percent starch. Enzyme digestion tests carried out in controlled experiments on cellulose/polymer grafts resulted in the cellulose in the grafts being degraded faster than cellulose alone.

Economic considerations: Some degradable plastics are currently on the market. Most of these products are photodegradable six-pack yokes. Some starch blends are used as lawn bags and agricultural mulches. Estimates are that on average, they cost 5 to 15 percent more than convential plastic products.

Estimated manufacturing costs for some of the degradable plastics are high. For example, manufacture of plastics with the A. eutrophus bacteria currently costs about $15 per pound, but expanded production is expected to lower to cost, possibly to half this level. This compares to about $0.65 per pound for conventional plastics. The starch-based polymer plastics are expected to sell at $2.20 per pound.

Because many of the degradable plastics utilize cornstarch, there is potential to increase demand for corn. The intended use for many of the degradable plastics is in packaging, since the life span of these products is very short. U.S. consumption of plastics for packaging is expected to reach 18.8 billion pounds by 1992. As a rough approximation of how replacement of these plastics with degradable plastics might affect corn demand, assume that the entire volume of packaging plastics is replaced by a 50 percent starch-plastic blend. The amount of corn needed to supply the starch is approximately 4 percent of the annual average production of corn. The economic analysis for such an increase would be similar to that for corn ethanol since both ethanol and degradable plastics utilize the starch portion of the grain. In both cases, coproducts produced would be corn gluten meal and corn gluten feed, which would compete with soybean meal in the high-protein livestock feed markets. As with ethanol, production costs of starch blends will depend somewhat on the price of corn and the value of the corn products.

This analysis however, assumes that corn starch will be the natural polymer of choice in natural polymer/synthetic polymer blends and/or grafts. Other natural polymers can be used such as cellulose and lignin. Both could be derived from corn stalks. However, both can also be derived from the paper and pulp manufacturing industry. As an example, the United States paper industry produces 33 million MT of Kraft lignin each year, which is primarily used for fuel, silage, or compost. Water-soluble graft copolymers can be made from this lignin. Potentially, these copolymers could be used in a variety of ways, including degradable plastics.

Social considerations: Each year the United States produces about 320 billion pounds of municipal solid waste, of which 7 percent (by weight) and 18 percent (by volume) are plastics. In 1987,55 billion pounds of plastic were produced and 22 billion pounds were discarded. More than half of the plastics discarded are in the form of packaging. Plastics are among the fastest growing components of municipal waste.

Utilizing degradable plastics is one tool in dealing with the large amounts of municipal waste produced in the United States each year. But by itself, it is not going to be enough. Other solutions will need to be found also. Some environmentalists are concerned about degradable plastics because of the lack of knowledge about the residues that remain after degradation. Additionally, there is concern that degradable plastics will adversely affect attempts to increase the recycling of plastics. Degradable plastics mixed with nondegradable plastics during recycling could contaminate the recycled plastic product. A major use envisioned for degradable plastics is in the food packaging arena. However, the Food and Drug Administration has not approved such use. Degradable plastics with high starch contents under appropriate conditions become moldy. Premature partial degradation might expose food to harmful organisms. Leaching of chemicals from the plastic might also occur. Considerable research is needed to determine the safety of degradable plastics for food uses.

Extent of research conducted: The General Accounting Office evaluated the extent of Federal support for degradable plastic research for 1988. A total of $1,729,000 supported 12 projects. The sources of funding were the Department of Agriculture ($941,000 for 4 projects), Department of Defense ($575,000 for 4 projects), Department of Energy ($150,000 for 3 projects) and National Science Foundation ($63,000 for 1 project). The USDA projects are developing degradable plastics utilizing corn starch and testing degradable plastics already available. DOD research is supporting research on bacterial production of plastics and degradable plastics that can be used for marine waste disposal. The DOE is supporting research mainly on cellulose and lignin copolymers and somewhat on starch copolymers. The NSF is supporting research on lignin copolymers.

Research on lactic acid-based plastics is being conducted at Battelle Memorial Institute (Columbus, OH) and Argonne (IL) National Laboratory. Research using *K.* pneumonia and vegetable oils is being conducted at Northern Regional Research Laboratory (Peoria, IL). Researchers at MIT, Univ. of Massachusetts, Office of Naval Research, Michigan State University, and University of Virginia are also working on developing biopolymers. Japan and Europe also have programs to produced biopolymers.

In addition to federally supported research, several private firms are interested in degradable plastics. Some already have products on the market. Some examples, by no means exhaustive, are:

1. Rhone-Poulenc, Ecoplastics, Princeton Polymer Laboratories, Du Pent, Union Carbide, Dow Chemicals, Mobil Chemicals, First Brands, Webster Industries, and SunBag all produce photodegradable additives and products.
2. Archer Daniels Midland, St. Lawrence Starch, Ampacet, AgriTech, Amko Plastics, Beresford Packaging, Polytech, and Webster Industries make starch-based masterbatch and products.
3. The Warner Lambert Company is producing starch-based polymers.
4. Montedison is producing thermoplastic starch resins that are alloys of cornstarch and synthetic resins.
5. ICI Biological Products is producing PHBV polymers.

SOURCES: *4,7,8,9,[illegible],11,14,21,25,26,29,30,31,32,33,35,36,42,44*

Biomass As a Chemical Feedstock Source

Crop: Corn primarily, but other starch and cellulose sources are possible

Major coproducts: Starch, oil, and gluten meal

Major uses: The starch is used to make commodity chemicals, the oil is used for edible purposes, and the gluten meal is used as livestock feed.

Replacement: Commodity chemicals derived from petroleum

Technical considerations: Technically, it is possible to produce fuel and most commodity chemicals from biomass (organic material produced by photosynthesis). Development of biomass as a source of fuel is impeded by: 1) the size of the United States fuel industry, 2) low energy content, 3) seasonality, and 4) the dispersed geographic locations of biomass. Use of biomass for commodity-chemical production would require fewer biomass resources and not put as much pressure on food sources. As an example, production of atypical commodity chemical at the rate of 0.5 million metric ton/year would require less than 1 percent of the United States corn crop. Thus, it seems reasonable to expect the greatest potential for biomass conversion to be for commodity-chemical production. Glucose is the primary starting material, obtained from starch derived from crops or Iignocellulose found in woody and fibrous plants. The glucose can be converted via chemical transformations into a variety of commodity chemicals. Starch is easier to work with but competes more directly with food uses for plants. Crops that could serve as a starch source include corn, cassava, and buffalo gourd (a potential new crop). Lignocellulose is more difficult to hydrolyze to sugars but maybe more available in larger quantities. Potentially it could be produced on land less suitable for good production and therefore not compete as strongly with food uses.

Economic considerations: The major constraint is economics. The petrochemical industry is highly integrated with multiple byproducts being used to produce other chemicals. In addition, large economies of scale allow for the relatively inexpensive production of fuel and many commodity chemicals. Some major commodity chemicals used in the United States will probably continue to be produced from petrochemical sources for some time. One example is ethylene. Production of ethylene from starch is complex and more expensive than cracking petroleum. Additionally, it is a large market. It is estimated that to provide 100 percent of the yearly ethylene market from starch derived from corn would require 50 percent of the corn crop. Producing ethylene, and similarly propylene, from starch seems impractical.

Chemicals other than ethylene and propylene may, however, have potential. Possibilities include ethanol, acetic acid, acetone, isopropanol, n-butanol, methyl ethyl ketone, and tetrahydrofuran. These chemicals are used in the production of other compounds. With some reduction in price, they might be competitive with petrochemical sources. Improvements in conversion efficiencies are needed. Other likely candidates are those chemicals that contain oxygen, since starch and glucose both contain about 50 percent oxygen. Possibilities include sorbitol used in the food processing industry, citric acid used in detergents, lactic acid used in thermoplastics and possibly biodegradable plastics.

The ability of biomass to compete with petroleum as a chemical feedstock hinges on rising petroleum prices.

As long as petroleum is fairly cheap, biomass will not be economically attractive. In addition, coal gasification and natural gas conversion can also be used to produce many of the same chemicals as biomass or petroleum cracking. Currently, natural gas is simply flared off as a waste product in petroleum drilling and processing in the Middle East. Potentially this could be used to manufacture chemical feedstocks. The United States is rich in coal. This coal is a more geographically concentrated resource than biomass. It is unlikely that as large a capital investment will be needed to fit processed coal into petroleum feedstock schemes as would be necessary for biomass. Additionally, many U.S. oil companies already have large investments in coal reserves. Environmental questions could have an impact on use of coal as a chemical feedstock. Land-use patterns and subsequent environmental impacts will be important if biomass is used to produce fuel and commodity chemicals.

Social considerations: Reasons given for using biomass to produce commodity chemicals include sustained production in many parts of the world, smaller and more geographically dispersed production facilities, conservation of nonrenewable resources, and the potential to use wastes that would otherwise need disposal.

Extent of **research conducted: The** Tennessee Valley Authority, in cooperation with the Department of Energy, conducts research to convert lignocellulose to chemicals.

SOURCES: 1,4,6,18,23,27,37,46

Appendix B References

1. Bajpai, Rakesh, Frisby, Jim, Hsieh, Fu-Hung, Iannotti, Gene, Kerley, Monty, Miles, John, Mueller, Rick, Vandepopuliere, Joe, and Van Dyne, Don, “Evaluation and Production of Feedstock Chemicals,’ paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
2. Barrier, John W., “Alcohol Fuels and TVA’s Biomass Research,’ *Forum for Applied Research and Public Policy,* Winter 1988, pp. 60-62.
3. Burnett, R.S., “Soy Protein Industrial Products,” *Soybean and Soybean Products,* vol. II, K.S. Markley (cd.) (New York, NY: Inner Science Publishers Inc., 1951), pp. 1003-1053.
4. Curlee, T. Randall, “Biomass-Derived Plastics: Viable Economic Alternatives to Petrochemical Plastics?,” *Materials and Society,* vol. 13, No. 4, 1989, pp. 381-409.
5. Dicks, Michael R., and Buckley, Katharine C., “Alternative Opportunities in Agriculture: Expanding Output Through Diversification,’ U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 633, May 1990.
6. Deane, William M., “New Industrial Markets for Starch,’ paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
7. Fanta, G. F., “Starch-Thermoplastic Polymer Composites by Graft Polymerization,” paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
8. Gibbons, Ann, “Making Plastics That Biodegrade,’’ *Technology Review,* February/March 1989, pp. 69-73.
9. Gilbert, Richard D., Lonikar, S.V., Fornes, R.E., and Rhodes, N., “Synthesis and Characterization of Biodegradable Polysaccharide Block Copolymers,” paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
10. Goldstein, Barry, Carr, Patrick M., Darby, William P., DeVeaux, Jennie S., Iceman, Larry, Shultz Jr., Eugene B., “Roots of the Buffalo Gourd: A Novel Source of Fuel Ethanol,’ *Fuels and Chemicals from Oilseeds: Technology and Policy Options,* American Association for the Advancement of Science Selected Symposium No. 91, Eugene B. Shultz, Jr., and Robert P. Morgan (eds.) (Boulder, CO: Westview Press, Inc., 1984), pp. 895-906.
11. Gould, J. Michael, Gordon, S.H., Dexter, L.B., and Swanson, C.L., “Microbial Degradation of Plastics Containing Starch,” paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18,1988.
12. Grethlein, Hans and Datta, Rathin, “Economic Analysis of Alternative Fermentation Route for the Production of Road Deicer from Corn,” poster paper at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988,
13. Grinnell, Gerald E., “Ethanol Fuel: The Policy Issues,” *Forum for Applied Research and Public Policy,* Winter 1988, pp. 48-49.
14. Hardin, Ben, “Farm Surpluses: Sources for Plastics,” *Agricultural Research,* October 1986, pp. 12-13.
15. Hassett, David J., “Diesel Fuel From chemically Modified Vegetable Oils,” *Fuels and Chemicals From Oilseeds: Technology and Policy Options, American* Association for the Advancement of Science Selected Symposium No. 91, Eugene B. Shultz, Jr., and Robert P. Morgan (eds.) (Boulder, CO: Westview Press, Inc., 1984), pp. 855-864.
16. Johnson, Dale W., “Non-food Uses of Soy Protein Products,” *World Soybean Research Conference III Proceedings* (Boulder, CO: West View Press, Inc., 1985).
17. Jordan, Wayne R., Newton, Ronald J., and Rains, D.W., “Biological Water Use Efficiency in Dryland Agriculture,” contractor report prepared for the Office of Technology Assessment, 1983.
18. Kaplan, Kim, and Adarns, Sean, “New Uses for Starch From Surplus Corn,“ *AgriculturalResearch,* October 1987, pg. 11.
19. Kaufman, Kenton R. “Testing of Vegetable Oils in Diesel Engines,’’ *Fuels and Chemicals From Oilseeds: Technology and Policy Options, American* Association for the Advancement of Science Selected Symposium No. 91, Eugene B. Shultz, Jr., and Robert P. Morgan (eds.) (Boulder, CO: Westview Press, Inc., 1984), pp. 143-175.

20, Keith, David, American Soybean Association, personal communication, 1989.

21. Kelly Harrison Associates, “A Survey of Potential New Corn Uses,” August 1986.

22, Lambert, Russ, Tennessee Valley Authority, personal communication, February 1991.

23. Lipinsky, E.S., "Chemicals from Biomass: Petrochemical Substitution Option,' *Science,* vol. 212, June 26,1981, pp. 1465-1471.
24. Lockertz, William, "Seed Oils as Diesel Fuel: Economics of Centralized and On-Farm Extraction,' *Fuels and Chemicals From Oilseeds: Technology and Policy Options, American* Association for the Advancement of Science Selected Symposium No. 91, Eugene B. Shultz, Jr., and Robert P. Morgan (eds.) (Boulder, CO: Westview Press, Inc., 1984), pp. 177-203.
25. Meister, John J., "Biodegradable Polymers and Plastics from the Corn Plant," paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
26. Meister, John J., Patil, Damodar R., Augustin, Cesar, Channell, Harvey, Li, Chin Tia, and Lai, James Z., "Utilization of the Polymer Content of the Corn Plant: Water-Soluble Lignin Graft Copolymers,' paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
27. Palsson, B. O., Fathi-Afshar, S., Rudd, D. F., Lightfoot, E.N. "Biomass as a Source of Chemical Feedstocks: An Economic Evaluation," *Science,* vol. 213, July 31, 1981, pp. 513-517.
28. *Science of Food and Agriculture,* Soybean Oil Inks, vol. 2, No. 2, July 1990.
29. Stiak, Jim, "The Down Side of Plastics," *National Gardening,* vol. 11, No. 12, December 1988, pp. 43-47.
30. Studt, Tim. "Degradable Plastics: New Technologies for Waste Management," *R & D Magazine,* March 1990, pp. 50-56.
31. Swanson, C. L., Westhoff, R. P., Deane, W.M., "Modified Starches in Plastic Films," paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
32. Thayer, Ann M., "Degradable Plastics Generate Controversy in Solid Waste Issues," *Chemical and Engineering News,* June 25, 1990, pp. 7-14.
33. Thayer, Ann M., "Solid Waste Concerns Spur Plastic Recycling Efforts,' *Chemical and Engineering News,* Jan. 30, 1989, pp. 7-15.
34. Thompson, James and Smith, Keith, "History of Industrial Use of Soybeans," paper presentation at American Oil Chemists Society Annual Meeting, Symposium on Value--added Products from Protein and Co-Products, May 1989.
35. U.S. Congress, General Accounting Office, *Degradable Plastics: Standards, Research and Development,* GAOI RCED-88-208, (Gaithersburg, MD: U.S. General Accounting Office, September 1988).
36. U.S. Congress, General Accounting Office, *Alcohol Fuels: Impacts from Increased Use of Ethanol Blended Fuels, GAO/RCED-90-156,* (Gaithersburg, MD: U.S. General Accounting Office, July 1990).
37. U.S. Congress, Office of Technology Assessment, *Commercial Biotechnology: An International Analysis,* OTA-BA-218, January 1984.
38. U.S. Department of Agriculture, "Marketing Potential for Oilseed Protein Materials In Industrial Uses," Technical Bulletin No. 1043, 1951.
39. U.S. Department of Agriculture, Office of Energy, "Fuel Ethanol and Agriculture: An Economic Assessment," Agricultural Economic Report # 562, August 1986.
40. U.S. Department of Agriculture, "Ethanol: Economic and Policy Tradeoffs," January 1988.
41. Wallace, Arthur and Wallace, Gam A., "Potential for Starch-Based Water Soluble Copolymers as Conditioners for Improving Physical Properties of Soil,' paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
42. *Wall Street Journal,* Oct. 13, 1988.
43. Wing, R. E., 'Non-chemically Modified Corn Starch Serves as Entrapment Agent," paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18, 1988.
44. Wool, Richard P., "Biodegradable Plastics from Cornstarch," paper presented at the Second National Corn Utilization Conference, Columbus, OH, Nov. 17-18,1988.
45. Wu, Lawrence and Shiley, Richard H., Illinois State Geological Survey, "Removing Sulfur From Coal: Ethanol Desulfurizaiton,'' March 1990.
46. Zerbe, John I., ''Biofuels: Production and Potential," *Forum for Applied Research and Public Policy,* Winter 1988, pp. 38-47.