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Alternate Industrial Feedstocks from Agriculture[1]

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Before the rapid development of the petrochemical industry, many feedstocks for manufacturing paints, plastics, fibers, lubricants, adhesives, and a host of other products were derived from agriculture. Good examples are linseed, castor, tung, tall, and soybean oils; natural rubber, gums, starch and cellulose, and many sources of fiber from the plant kingdom, as well as hides, bones, and fats and oils from the animal kingdom. In addition to these traditional agricultural materials, several new plant sources have been developed through new crops research. Also, new ways have been developed for converting existing agricultural products to better chemical intermediates. Availability of farm land, economics of crop production, and competition with petroleum are such that agriculture should be considered seriously as a viable alternative for at least part of our chemical feedstock requirements.

Many chemical products can be manufactured from various sources of feedstocks; however, sometimes such feedstocks are changed to satisfy economic or other supply-and-demand criteria. For example, at one time nylon 6 or 66 was produced in Europe almost exclusively from coal, but then a switch was made to petroleum-derived caprolactam or hexamethylene diamine and adipic acid. Conceivably, nylon 66 could be made from agriculturally produced petroselinic acid, which can be split into lauric acid and adipic acid. The latter could then be converted further, while lauric acid would be a valuable by-product. Many other examples could serve as well.

In addition to importing approximately 50% of our petroleum requirements, we also import many foreign agricultural products for chemical feedstocks, such as high erucic rapeseed (*Brassica napus*) oil, castor (*Ricinus communis*) oil, short chain fatty acids from coconut (*Cocos nucifera*) distillates, wood-derived paper, and natural rubber (*Hevea brasiliensis*). During the past 5 yr, raw material supplies and their possible replacements have been scrutinized more carefully than ever before. Continuing price increases, spot shortages, poor balance of import-export payments, and the threat of political embargoes or natural calamities have already had a strong impact on our production processes and general economy. Although petroleum-derived energy and chemicals will be the mainstay of our economy for some time to come, the whole world is looking seriously at various options and alternatives.

The ample availability of coal in some parts of the world, including the United States, makes it a viable alternative to oil for energy and chemicals production. As a matter of fact, in our zeal for developing and conducting research, we often forget how much already is known about coal and its conversion to energy and

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TABLE 1. CHEMICAL CONSTITUENTS OF PLANTS.

Fats and oils trigiycerides, liquid wax	Hydrocarbons rubber, turpentine
Starches paper and textile sizes	Cellulosics fiber and chemicals
Sugars substrate for fermentations	Lignins phenolics, resins
Gums varied physical and chemical properties for thickening of liquids	Waxes carnauba, candelilla
Proteins zein, gluten	Other alkaloids, tannins, steroids

chemical products. Germany fought World War II rather successfully on a coal-based economy that was developed in the 1920–1940 era. In this light, it should be remembered that also agriculture and forestry have served mankind well for the production of many chemical intermediates and other products not directly related to food and feed. Cultivated plants and domesticated animals have provided us with fiber for textiles and paper and with chemicals for paints, plastics, adhesives, lubricants, surfactants (soaps and detergents), and a host of other products. Still, when agriculture is considered as a major source for manufacturing feedstocks, it appears to take a backseat to other available alternatives. This paper reviews some critical elements pertinent to technical feasibilities, economics, and other requirements for including domestic agriculture as a viable option in our quest for feedstock alternatives.

PLANT AND ANIMAL PRODUCTS

The plant and animal kingdoms provide us not only with food and feed (in the form of carbohydrates, proteins, fats, and oils) but also with the main ingredients for many industrial products, either from direct use or from by-product wastes. Table 1 shows the multitude of chemicals found in plants. A similar but slightly different scheme can be developed for the animal kingdom (Table 2).

Although animals traditionally have been domesticated for specific purposes, with food being the most important, we learned early to utilize many of the slaughter by-products in manufacturing processes. The same is true for plant by-products. For example, flax (*Linum usitatissimum*) is grown mainly for linseed oil and meal, but the by-product straw is used for linen and specialty paper. A whole chemical industry is based on corncobs as feedstock. Turpentine is a well-

TABLE 2. CONSTITUENTS OF ANIMALS.

Fats and oils—tallow, lard, fish oil	Proteins—collagen, casein
Hides and intestines—leather, membranes	Bone—glue, fertilizer
Fiber—wool, feather down	Other—drugs, serums

used by-product of the wood pulping industry. Cottonseed (*Gossypium hirsutum*) has been developed into food and feed by-products, where the crop is primarily raised for textile fiber. Although this approach to utilizing by-product wastes to good advantage could be extended further, plants also can be grown specifically for the production of industrial feedstocks. Castor beans and tung (*Aleurites fordii*) nuts are good examples of such crops.

ABUNDANT AGRICULTURAL SOURCES FOR FEEDSTOCKS

Traditionally, agricultural products were used with little or no chemical modification in manufacturing processes. For example, linseed oil has been used directly or after simple heatbodying in paints by grinding pigments directly into the oil and adjusting viscosity by addition of a small amount of organic solvent. Later, it was found that chemical modification of the drying oil to alkyds resulted in even better preformance. Fatty acid sodium salts have served us well as soaps. Starch has been used with little chemical modification in paper and textiles. Castor oil has been used without modification in lubricant formulations. Even with the advent of synthetic rubbers, natural rubber has maintained its prominence. However, along with the great strides in organic syntheses related to the petrochemical industry, chemical knowledge for converting natural products to improved industrial feedstocks also has increased. As a result of new crops research and development, new agricultural feedstocks can be produced that have not been available until recently. Fats and oils for nonfood uses are available in abundance, and production can be increased if necessary. Starch is still one of the cheapest chemicals and can be utilized to greater advantage. Even industrial proteins could be made in larger quantities. New annual crops for fibers and new oilseed crops for production of unique fatty acids could be cultivated rapidly.

Fats and oils

USDA's Regional Research Centers have developed many new chemical routes to make traditional fats and oils into more desirable intermediates and end products. Emphasis has been given to soybean (*Glycine max*), linseed, cottonseed, and other oils of trade, as well as to tallow and lard. These studies have shown that such chemical modifications can lead to high-quality end products such as paints, plastics, lubricants, or surfactants. Several published reviews give a good account of the possibilities (Pryde, 1979; Princen, 1979a; Pryde, 1980; Linfield, 1978). Modification of unsaturated fatty acids or their triglycerides to vinyl ethers (Teeter, 1963), polyester amides (Schneider and Gast, 1979), and epoxy (Swern and Parker, 1957), formyl (Frankel and Pryde, 1977), or cyclic (Friedrich and Gast, 1967) derivatives as replacements for petrochemical feedstocks looks especially promising.

Research on emulsification and solubilization of drying oils and their derivatives has shown that water-based coatings systems can be designed with the same qualities so highly regarded in modern latex paints (Princen, 1974). Use of linseed oil has been extended to include solvent- and water-based formulations to cure and protect concrete on roads and bridges against freeze-thaw damage (Best et al., 1974).

Starch and other polysaccharides

As indicated, starch can be used directly for numerous applications, but chemical modifications have led to many new uses (Doane, 1978). Graft polymerization has provided us with "super slurper," a product with unequaled water-absorbing properties (Doane, 1979). Already it is being used as a seed coating to aid germination and seedling vigor and as an absorbent in diapers, surgical bandages, and other medical applications. Additional applications are developing rapidly.

Starch-derived polymer films have found use as soluble laundry bags and degradable mulches for vegetable crop production (Otey, 1977). Insoluble starch xanthate is one of the most prominent materials for removing and recovering heavy metals from waste water in electroplating processes (Wing et al., 1978). Other starch derivatives, such as cationic starch, make improved sizings for paper and textiles (Hamerstrand et al., 1979). Coprecipitation of starch xanthide and *Hevea* rubber latex results in a powdered rubber that does not have to be milled like slab rubber, resulting in great energy savings in rubber processing (Conway and Sohns, 1975). Similarly, starch can be used for slow-release formulations of pesticides (Doane et al., 1977). Starch and its fragments also can be used advantageously in the manufacturing of urethane foams in lieu of pentaerithritol and other more costly polyols (Otey et al., 1978). All this is possible because of the low cost of high-purity starches from the grain milling industries. No doubt some of these technologies also can be transferred to modify cellulosic materials that are abundantly available as agricultural by-products. In one form or another, cellulosics always have been used extensively in paper and textiles. Cotton, linen, sisal, and many other fibers have been used for clothing, yarn or rope. Wood fibers are the main source for paper production. The xanthate process made it possible to solubilize cellulose for fiber-spinning technology.

Other polysaccharide conversions that have already been well tested include the microbial polysaccharides (Sandford and Laskin, 1977). They can be manufactured in large quantities through fermentation processes and have been used extensively as food and industrial thickening agents (xanthan gum) and as blood extenders (dextran). Several related products are now offered by manufacturers. Plant gums are predominently polysaccharides and have prominent applications in industrial and food processing.

Industrial proteins

Wheat gluten and corn-derived zein are 2 good examples of plant proteins used in industrial applications (Krull and Inglett, 1971; Reiners et al., 1973). However, their production and demand have gone down slowly but steadily. Casein and collagen are animal derived and have been used for many purposes, such as thickeners and glues (Donnelly and Simmons, 1979; Southward and Walker, 1979). Again, demand has decreased with the development of man-made polymers. However, all these proteins can be reinstated as prominent feedstocks if the need arises.

Hydrocarbons

Hevea and guayule (*Parthenium argentatum*) are the most prominent and best known producers of natural rubber. Even in this day of well-developed synthetic

rubber technology, the United States imports approximately 1.6 bill lb of *Hevea* rubber each year and could use more. That is probably the main reason for the strong renewed interest in guayule as a domestic rubber crop.

Turpentine, rosin, tall oil, and other naval store products from the wood pulping industry have always been used to good advantage for chemical manufacturing and are still abundantly available at relatively low price.

New crops development

USDA has maintained an active research program on new crops development for the past 20 yr, with main emphasis on industrial oilseed and fiber crops. This program has involved chemical screening of wild plant species from anywhere in the world for seed oil or fiber quality and yields, agronomic screening for crop potential, and genetic studies of promising species. Approximately 7,000 species have been screened for seed oils, 500 for fibers for paper production, 1,200 for antitumor agents, 100 for natural pesticides, 400 for hydrocarbon content, and 300 for proteins. Many plants have been found suitable for crop production for obtaining unique fatty acids not normally found in traditional crops, such as long-chain, short-chain, hydroxy, epoxy, and conjugated polyunsaturated fatty acids, or acids with special location of unsaturation (Princen, 1979b).

The fiber-screening program has uncovered excellent candidates of annual plants that can produce up to 10 times the amount of fiber per year per acre now obtained from hardwoods and softwoods. Several species have been studied in all their production and utilization aspects. Especially kenaf (*Hibiscus cannabinus*) has now come to the point where production, pulping, and papermaking technologies are all in place for immediate commercialization (Bagby, 1977).

The recent program on hydrocarbon screening has identified many plant species that may be good future sources of rubber, in addition to *Hevea* and guayule (Buchanan and Otey, 1979). This screening program was initiated by studying plants that had already been identified as good fiber sources, with the idea of developing crop plants for multiple use purposes, as is the situation with flax or cotton.

The summation presented above on existing and prospective crop plants is not meant to be all-inclusive, but merely serves as an example of the existing technological knowledge that could make any shift in feedstocks rather easy, if and when such is desired or required. The more pertinent problems of shifting feedstocks probably lie in various aspects of their production, such as land availability, economics, and need for increased involvement by the chemical industry.

LAND AVAILABILITY AND NEED

Total annual petroleum use in the United States at 18 mill barrels per day is:

$$18 \times 10^6 \frac{\text{barrels}}{\text{day}} \times 300 \frac{\text{lb}}{\text{barrels}} \times 365 \frac{\text{days}}{\text{yr}} \sim 2 \times 10^{12} \text{ lb/yr.}$$

Producing the equivalent energy and chemicals from agriculture would require up to 10^9 acres of farm land, assuming an average yield of 2,000 lb of usable product per acre. These usable products could vary from vegetable oil for diesel fuel to

fermentation alcohol from grain or sugarcane or to any other product derived in some way from biomass.

At present, about 470 mill acres are ready and available in the United States for cropland, of which about 360 mill acres are cropped each year (Agricultural Statistics, 1978). The remaining acreages are not used annually for various reasons. It has been established that an additional 90 mill acres in the United States could be developed into prime agricultural land (Lee, 1978), so that total cropland availability could be increased to about 560 mill acres if the need arises. This number does not include any use of marginal lands, such as desert or marsh land. This land is not enough to satisfy all the needs now met by petroleum, so it appears that agriculture should not be considered as the sole source for all our energy and chemical needs. However, these figures indicate that agriculture could produce at least a part of these needs.

Considering that about 8% of our oil and natural gas is used for petrochemical feedstocks, this amount could be produced from agricultural crops rather easily. Of the 200 mill acres of cropland that could be made available, only about 60–80 mill acres would be required. In addition to this acreage of good farmland, other land could be utilized by developing crops that do not require high-quality land or good climatic conditions. For example, guayule and jojoba (*Simmondsia chinensis*) can be produced on desert land of the Southwestern States that is not suited for other cropping purposes. Other areas of the United States have specific problems that make competition difficult in the production of traditional crops, and these acres could be advantageously diverted to different crops. Stripmine land may not be acceptable for raising food and feed, because of heavy metal and other contamination, but it could be diverted to produce industrial crops. Good crop rotation practices also would make land available, once industrial crops for chemical feedstocks are grown on a regular basis.

What land requirements have to be met for specific industrial crops? The answer to this question indicates that these requirements are not as high as has been believed. Table 3 provides some examples to show the impact of a few

TABLE 3. SOME DOMESTIC CROP NEEDS TO REPLACE IMPORTED FEEDSTOCKS OR FINISHED PRODUCTS.

Potential domestic crop	To replace	Quantity imported or desired	Value	Acres needed
Crambe abyssinica	High erucic rape oil	15×10^6 lb	\$ 6×10^6	30,000
Simmondsia chinensis, jojoba	Sperm oil and waxes	60×10^6 lb	\$ 60×10^6	60,000
Lesquerella spp.	Castor oil	100×10^6 lb	\$ 50×10^6	200,000
Vernonia galamensis, *Stokesia laevis*	Epoxy oils	150×10^6 lb	\$ 100×10^6	250,000
Parthenium argentatum, guayule	Hevea or synthetic rubber	$1,000 \times 10^6$ lb	\$ 800×10^6	1,000,000
Hibiscus cannabinus, kenaf	Newsprint	6×10^6 tons	\$ $2,500 \times 10^6$	1,000,000
Assorted oilseeds	Petrochemicals for coatings	$1,000 \times 106$ lb	\$ 400×10^6	2,000,000
			\$ $4,000 \times 10^6$	4,500,000

domestic crops on land needs, thereby creating an improved import-export balance and domestic economy.

This simple compilation shows that only 4.5 mill acres of land, including over 1 mill acres of marginal land, can generate $4 billion worth of goods that are now obtained by importing foreign agricultural or petroleum-related feedstocks. Not included in this figure are the values of produced by-products and the general economic advantages for domestic agriculture and industry.

The information provided here indicates that the United States has the land needed to provide us with chemical feedstocks for a long time to come, with additional land left to produce other crops for a sizable part of our energy or food needs.

ECONOMICS

Two main questions have to be answered under the heading of economics: (a) can industrial crops compete with conventional crops in production costs and profits on the farm; and (b) can the end product to be used as an alternative feedstock compete pricewise with petrochemicals or other imported materials used now for the same purpose? Both questions are complex and vary from crop to crop and from location to location.

A farmer who can reliably produce between 200 and 300 bu of corn per acre in the Midwest is not a good candidate to get involved in other crops, but he is the exception rather than the rule when it comes to yields and profits. Many farming areas in the United States could benefit from increased choices of crops to grow. These include such areas as western Kentucky and southern Missouri, southern Georgia and northern Florida, western Texas and New Mexico, Oregon and Washington, Montana and North and South Dakota. Most of these areas have difficulty producing traditional crops in competition with other parts of the country. For example, in western Kentucky farmers can raise about 30 bu of wheat per acre for a return of about $120. First attempts to grow crambe (*Crambe abyssinica*) resulted in an average yield of 1,800 lb/acre. At a price of 11.5 c/lb, a value that makes crambe oil competitive with imported high-erucic rapeseed oil, the farmer's intake can be increased to over $200 per acre. In Southern States, where corn producers rarely reach average yields, 60 bu of corn bring the farmer about $200 per acre. If he could grow kenaf instead, his return could be doubled, and the price of newsprint produced therefrom would still be substantially less than imported paper. Flax has been used traditionally as a standby crop in the North Central States, but it could be made more profitable there or in many other parts of the country if we chose to rely more heavily upon linseed oil in our manufacturing processes. These few examples indicate that many industrial feedstock crops could be beneficial to the farmer.

The second question relates the economy of agricultural products to conventional feedstocks. Even at today's inflated prices, imported petroleum costs only about 13 c/lb; however, a lot of high-priced chemistry and chemical engineering are required to convert this raw oil to usable chemical intermediates. If one compares costs for such intermediates with those of agricultural products, which often can be used as is, the economic aspects can hardly be blamed for the reluctance to change feedstocks. The same appears to be true for conversions from imported to domestic agricultural feedstocks. Table 4 shows some price

TABLE 4. SOME PRICE COMPARISONS FOR PETROCHEMICALS AND AGRICULTURAL PRODUCTS, DECEMBER 1979.[a]

Petroleum-based chemicals	$/lb	Fats and oils	$/lb
Acrylonitrile-butadiene-styrene rubber	0.67–0.72	Tallow	0.20
Acrylonitrile	0.30	Soybean	0.255
Acrylic acid	0.44	Palm	0.33
Methacrylic acid	0.68	Cod	0.235
Chlorinated rubber	0.99–1.35	Lard	0.21
Phthalic anhydride	0.40	Lard oil	0.37
Butadiene	0.30	Fish	0.29
Styrene	0.40	Linseed	0.29
Polyethylene	0.39–0.54	Castor	0.545
Polypropylene	0.38–0.41	Tung	0.51
Polycarbonate resin	1.20	Tall (refined)	0.21
Polyester resin	0.51–0.56	**Carbohydrates**	
Polyvinyl alcohol	0.67–0.78	Starch	0.08–0.10
Polyvinyl acetate	0.40–0.50	Dextrin	0.155
Polyvinyl chloride	0.39–0.50	Sorbitol	0.36–0.64
Epoxy resin	0.93	Collodion	0.45
Polystyrene	0.46–0.49	Sucrose (refined)	0.26
Styrene-acrylonitrile	0.51	Cellulose acetate	0.88
Montan wax (from lignite, peat, etc.)	0.41–0.48	Carboxyl methyl cellulose	0.76–0.91
Proteins		**Gums**	
Bone glue	0.64–0.68	Ester gum	0.22
Hide glue	0.73–1.14	Guar (*Cyamopsis tetragonolobus*)	0.45–0.62
Casein	0.87–0.90	Arabic (*Acacia senegal*)	0.72–1.14
Gelatin	0.90–2.20	Locust bean (*Ceratonia siliqua*)	1.05
Zein	4.35	**Hydrocarbons**	
Waxes		Turpentine	0.06
Carnauba (*Copernicia cerifera*)	0.95–1.75	Natural rubber	0.80
Candelilla (*Euphorbia antisyphilitica*)	1.30–1.50	Shellac	1.65–2.15
Bee	2.50–2.65		

[a] Chemical Marketing Reports, Dec. 24, 1979.

comparisons. When these prices are compared with those of 3 yr earlier, it is immediately obvious that the decline of the dollar value has resulted in much sharper price increases for imported agricultural products than for petrochemicals. Castor, palm, and tung oils, as well as natural rubber, have all doubled in price, whereas petrochemicals have increased much less.

CONCLUSIONS AND DISCUSSION

Tradition appears to be a major obstacle to increasing the use of alternative feedstocks from agriculture. During the past 30 yr, we have become accustomed to being able to order a tank car of this or so many barrels of that item by simply dialing a telephone number. A few days later the material can be delivered. Only in times of stress, such as a petroleum boycott, do we notice the facility with which such transactions normally take place. Another part of tradition is our

knowledge about the feedstocks used. During the past 30 yr, chemists and engineers have been trained almost exclusively in the utilization of petrochemicals and imported commodities. Few people know and understand the chemistry of coal or agricultural feedstocks used before that time.

In addition to technological obstacles, there are legal, commercial, and logistical aspects as well. Many industries that at one time depended heavily upon agricultural commodities for feedstocks have given up their expertise over the years in favor of reliable petrochemicals. Contracting practices, following crops through production and harvest, commodity trading, quality control, processing facilities, and knowledge of chemical modifications have gradually declined.

It must be admitted that domestic agriculture as a source for feedstocks is much more complex than what we have become used to. Even the purchasing of imported agricultural products is much simpler, since we tend to purchase only that part of the crop that is needed, be it a vegetable oil, free fatty acids, fibers, or their finished products such as paper or textiles. In such situations we leave the worries of production, processing, and by-product utilization to the countries of origin.

Complexity of the supply-and-demand system of agricultural production is also a major problem. Major agricultural commodities are traded on an open market where the farmer has an assured outlet, the user has an assured supply, and the only issue for negotiation is the price. However, some food-related industries have their raw materials, such as sweet corn, pumpkins, or mint, grown under contract. This latter approach will probably also be needed for most industrial crops to be acceptable to all involved. Under such conditions the chemical industry would have a guaranteed supply at a guaranteed price, and the farmer would have fewer problems in planning, producing, and selling his crops. Several new crops have been developed to the point where they could go into production almost immediately, but it has been impossible to break through the commercialization barrier for precisely these reasons.

Over the past 20 yr, our research and development experiences and our association with the production, processing, and utilization branches of agriculture in the fields of conventional and new crops indicate that any desired change in feedstocks will require concentrated efforts on the part of all parties involved. It is our belief that the Federal Government could play a major role in guiding such efforts by accepting a leadership position, drawing all interested parties together, and developing guaranteed loan programs for a limited time, so that everyone involved will have an opportunity to get acquainted with all ramifications of the production and utilization of the feedstock. An attempt was made to start such a 3-yr program for crambe. In this program, a total of 2,000–4,000 acres of crambe could have been grown in several areas of the country, under conditions that make the farmers familiar with the production aspects and assure the industrial cooperators a continued supply of oil without major risks. After this period, the free market can be allowed to take over. If successful, this program could have served as a model for other crops that could be used advantageously and are ready for commercialization. Until now, attempts to initiate such a program have failed. However, one company has taken the initiative and did contract with farmers to produce 1,000 acres of crambe. The private sector is also moving rapidly towards commercial production of kenaf for newsprint. Similar break-

throughs in the area of new chemicals from established crops indicate that interest is increasing rapidly, and that for a number of the developments described here, no government assistance is required after all.

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