New Crop Developments for Industrial Oils[1]

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ABSTRACT

Traditional industrial fats and oils are derived from inedible tallow or lard, fish and whale oil, and a small group of plant oils, including linseed, soybean, castor, tung, tall, and rapeseed oil. A group of new crops and prospective new crops is available to be utilized advantageously for the production of renewable industrial resources. Some of these plants have been studied extensively from germplasm variation through crop production and processing to evaluation of the final oil and meal products. Others are not developed that far yet. Case histories on *Crambe, Limnanthes, Lunaria* (long chain acids), *Lesquerella* (hydroxy acids), *Stokesia* and *Vernonia* (epoxy acids), *Calendula* (conjugated unsaturation), *Cuphea* (short chain acids), jojoba (liquid wax esters), and *Foeniculum* (petroselenic acid) indicate that many obstacles must be overcome to arrive at success.

INTRODUCTION

The 1973 oil embargo and subsequent price increases and shortages have made the chemical industry increasingly concerned with evaluating nonpetroleum sources of feedstock. Although there are several alternatives available for consideration, such as coal, oil shale, recycling, or importing of foreign agricultural products, the long term solution to the problem may be that of utilizing domestic agriculture and forestry for the production of renewable industrial resources.

It would require as many as 700 million acres of farm land (at an unrealistically high projected yield of 10 barrels of oil substitute per acre per year) to replace all of our petroleum products with agricultural commodities, such as "gasoline trees" or more conventional crops. Today the United States farms only 335 million acres for total crop production, so it becomes apparent that such a venture would not be feasible. Much of our energy needs will therefore have to come from other sources, such as nuclear reactions, coal, solar radiation, or wind driven power generators. Since only ca. 8% of our petroleum usage is for chemicals' production, the 60 million acres needed to produce replacement raw materials could be found more easily. Up to 140 million acres of established cropland are lying idle or are placed in pasture from year to year (1). In addition, 78 million acres have been identified as noncrop land with a high potential for development, and another 33 million acres have medium potential for conversion to cropland (2).

Although petroleum-based chemicals and consumer products have been most prominent during the last 30 years, animal fats, vegetable oils, and other natural products still play a significant role in the manufacture of coatings, adhesives, lubricants, surfactants, and plastics. Total industrial civilian consumption of fats and oils in the United States is 5 billion lb per year (3). Their use could be expanded easily in a technological sense. Also, the economical aspects and availability are such that a forced change to increased use of natural products could be accomplished without many major problems.

This paper will review the status of the more promising new oilseed crops, as well as discuss and speculate on some major changes that may be needed in government and private sector activities to successfully expand new crop developments to full scale production.

POTENTIAL NEW OILSEED CROPS

Over the past 20 years, USDA has had a strong research and development program on new crops for the production of industrial oils, fiber, gums, natural rubber, carbohydrates, alkaloids, and chemical intermediates. This program was initiated by I.A. Wolff and Q. Jones (4) in the late 1950s, mainly to alleviate overproduction and accumulated surpluses of traditional crops. Recently, surplus agricultural commodities and set-aside acreages have again been in the news, but now we face the additional burdens of a threatened petroleum shortage, an unfavorable import-export balance, and increasing health and safety regulations in the manufacture and use of chemicals.

USDA's research program has resulted in chemical screening of 6500 species of wild plants, and a significant number of excellent candidates for the production of unique, desirable seed oils (5-8). Some of these potential crops have been evaluated extensively and could be produced now, whereas others require additional research input.

Long Chain Fatty Acid Crops

Long chain fatty acids, mainly erucic acid, are used in the chemical industry at a level of 10 million lb per year, and rapeseed oil has traditionally been the main source. All high erucic rapeseed oil has been imported and is becoming in short supply because of the development of low erucic rapeseed for food purposes. Several plant species are now available to replace this diminishing source.

Crambe abyssinica. Crambe has been studied probably in more detail than any other prospective new oilseed crop, and could be an excellent source of erucic acid today. Crambe seed contains 30 to 40% oil, of which up to 60% is erucic acid. The oil has been evaluated successfully for the manufacture of lubricants (9,10), plasticizers (11,12), nylon 1313 (13,14), and other applications (15). Although the meal contains glucosinolates, natural toxicants that are common in vegetables and seed meals from plants of the family Cruciferae, it has been shown that proper conditions during seed processing make the meal useful for beef cattle feeding (16,17). FDA clearance for its use in interstate commerce has been requested. Crambe has been grown semicommercially at levels of several thousand acres from North Dakota to Texas, and from California to Connecticut, as well as in other countries, with yields varying from 600 to 4000 lb of seed per acre. Typical yields are 1600 to 2400 lb under normal agronomic practices and conditions. Processing has been carried out by both traditional pressing and solvent extraction techniques, in which care must be taken in enzyme deactivation (18) and/or glucosinolate removal (19).

Genetically, there appears to be little variability in wild Crambe seed, so it may not be possible to breed for low glucosinolate or higher erucic acid-containing seed lines. Fertilizer requirements, cultivation, and harvesting practices for Crambe production are well understood. As a spring crop, its seed can be harvested from 90 to 100 days after planting (20). Some studies have been undertaken to evaluate its potential for double cropping.

Limnanthes alba. Meadowfoam and other *Limnanthes* species are native to the American northwestern states and

[1]Presented at the AOCS Meeting, St. Louis, Missouri, May 1978.

have been evaluated as potential crops for the production of long chain acids. They contain typically up to 33% oil, with a minimum of 95% C_{20} and C_{22} monoene and diene acids (21). *L. alba* has been selected at Oregon State University in cooperation with USDA as a promising species because of its upright growth habit and its general agronomic performance (22), and has advanced to seed increase trials and small production plots. The northwestern states are actively exploring alternate crops, for example, to replace grass seed production in the Willamette Valley in Oregon. Those states are net importers of proteinaceous feed meals, and they can expect chemical industrial expansions due to development of Alaskan oil fields. Therefore, *Limnanthes* has an excellent chance for early success. However, unlike the extensive studies that have gone into development of uses for crambe oil and meal, much less has been done to explore the best ways of utilizing the unique acids of *Limnanthes* oil (23-25), nor has the meal been tested sufficiently through animal feeding studies to evaluate fully the effects of glucosinolates and possibly other toxicants (26).

Brassica napus and campestris. Plant breeding efforts in Canada successfully produced low glucosinolate, low erucic acid rapeseed for food and feed purposes, and breeding programs are now underway to develop a low glucosinolate, high erucic rapeseed for the production of an industrial oil. One research program has been carried out by W. Calhoun at Oregon State University under the auspices of USDA and in cooperation with the Northern Regional Research Center (27). Several seed lines have been obtained with 40% oil, 55% erucic acid, and 1% glucosinolate. The facts that rapeseed can be easily separated from its hull and that the meal may be more valuable if low glucosinolate levels can be achieved genetically may make such a crop ultimately more desirable than crambe for erucic acid production. However, development of crambe is farther along and it could be used immediately, whereas the rapeseed lines still have to be evaluated for their genetic stability and agronomic performance.

Lunaria annua. Money plant or Honesty has been grown commercially as an ornamental and for dried flower arrangements and has the potential of producing up to 5000 lb of seed per acre. The seed contains up to 40% oil with 42% C_{22} and 21% C_{24} monoene acids (28). Normally, the species is grown as a biennial, but annual seed lines are available (29). *Lunaria* is grown best in northern areas, with long daylight during the summer months required for abundant flowering and good seed production. Seed production from annual lines is now being evaluated on test plots in Alaska.

Hydroxy Acid Crops

Imported castor oil is the main source for hydroxy fatty acids. Annual imports amount to ca. 100 to 150 million lb of oil. Several potential crops could be used to replace castor oil in the United States.

Lesquerella species. About 20 species of Lesquerellas are native to central and south central United States. They produce seed with 20 to 40% oil and from 50 to 74% hydroxy fatty acids. The most prominent acid is lesquerolic acid (C_{20} monohydroxy monoene), but some species contain mainly C_{18} monohydroxy diene acid instead (30). Some Lesquerellas grow so densely in the wild that seed has been harvested by combine from such stands. Preliminary genetic and agronomic studies have been undertaken (31), as well as preliminary chemical evaluations of the oil and seed meal (32-34). Seed yields of more than 1800 lb/acre have been obtained in experimental plots. Although Lesquerella oils are lower in hydroxy fatty acids than is castor oil (typically 80 to 87%), their seed meals resemble rapeseed and crambe meals in toxicological properties (35) and should be more suitable as animal feed than the dangerously toxic castor seed meal.

Other unique hydroxy acids. Several plant species are known that have potential as sources of special hydroxy fatty acids. For example, *Cardamine impatiens* seed contains 33% oil, of which ca. 25% consists of a mixture of mainly C_{22} and C_{24} dihydroxy acids (36). *Chamapeuce afra* seed contains 20 to 28% oil with up to 35% trihydroxy C_{18} acids (37), and *Dimorphotheca sinuata* seed has 31 to 44% oil with 67% of monohydroxy conjugated diene C_{18} acid (38). The results of preliminary agronomic evaluations of some of these plant species are favorable (39,40).

Epoxy Fatty Acids

U.S. consumption of epoxy fatty acids in plastics, coatings, adhesives, and related products is ca. 140 million lb annually and growing. The epoxy acids are produced from commercial vegetable oils, such as soybean or linseed oils, through a process that is expensive in both energy and economics. However, many plants produce seed which contains such epoxy oils (41). Some of these plants have definite crop potential.

Vernonia anthelmintica. This plant species from India was studied extensively when it appeared promising as a future source of epoxy oil. Its seed contains 23 to 31% oil with 68 to 75% epoxy acids. The oil was evaluated as a stabilizer in polyvinylchloride (42), and extensive genetic and agronomic evaluations were made (43,44). The latter were disappointing due to poor seed retention and unexpected diseases, but observed variations in the germplasm base may allow these shortcomings to be overcome.

Vernonia pauciflora. This species from East Africa has 40 to 42% of seed oil with 73 to 80% epoxy acid content. It has recently been grown successfully in Kenya. A 1-ounce sample, provided by USDA, was increased to more than 200 lb in two growing seasons without obvious problems (Bates, L., private communication). Part of the seed has been made available to USDA for processing studies and chemical evaluation of the oil. *Vernonia* species appear to require short day length for good flowering and seed setting; so successful production in the United States is most likely to occur in the southern states.

Stokesia laevis. Stokes' Aster is a native perennial of the southeastern United States that has been used as an ornamental. The seed contains 36 to 49% oil with 75% epoxy acids. Preliminary seed yields are estimated from 300 to 1000 lb/acre (45). Agronomic evaluation indicates both strong and weak characteristics. *Stokesia* is a perennial, which may be a plus in that it does not require annual plowing and seeding as do most crops. However, stands become established only slowly. Other sources of epoxy oils are found in the genera *Crepis, Erlangea, Cephalocroton,* and *Euphorbia* (41).

Conjugated Unsaturation

Tung oil has often been used industrially when conjugated unsaturation is desired. Such double bond configuration also can be obtained through isomerization of linseed and other oils of high unsaturation. At one time tung oil was deemed important enough to try to develop tree plantations in the southern states. However, the attempt was short lived because of the vulnerability of the trees to freezing temperatures and tropical storms. Several annual plant species are known to produce similar oils, and crop development from these species would circumvent the problem with domestic tung nut production. Good examples of annual plants with conjugated unsaturation are: *Valeriana officinalis* with 26 to 34% seed oil and 40% 9,11,13 unsaturation; *Calendula officinalis* with 40 to 46% oil and 55% 8,10,12 unsaturation; *Centranthus macrosiphon* with 28 to 32% oil and 65% 9,11,13 unsaturation;

Impatiens edgeworthii with 50 to 53% oil and 60% 9,11,13,15 tetraene unsaturation; and *Dimorphotheca sinuata* with 31 to 44% oil and 60% 10,12 conjugated unsaturation plus an additional OH group. This latter fatty acid can be dehydrated, as is often done with castor oil, to arrive at a conjugated triene.

Only a preliminary evaluation has been carried out to determine crop potential for some of these prospective oilseeds (39), but variation in the germplasm base appears to be sufficient to start a concerted program if warranted by the needs of the chemical industry.

Short Chain Fatty Acids

Industry has always made extensive use of short chain fatty acids for a variety of end uses. The normal C_8, C_{10}, and C_{12} saturated fatty acids are produced mainly from coconut and other palm kernel oils, in which C_8 and C_{10} acids are found only at levels of 6 to 10%. Lauric acid makes up ca. 45 to 50% of such oils. Recently the price for short chain acids has increased rapidly, and new sources may become desirable. Early screening work has identified the genus *Cuphea* (46,47) as a group of plants with high levels of short chain fatty acids. Typical results are *C. carthagenensis* with 33% oil and 18% C_{10} plus 57% C_{12}, *C. painteri* with 36% oil and 73% C_8 plus 24% C_{10}, *C. ignea* with 34% oil and 87% C_{10} and 3% C_8, and *C. llavea* with up to 30% oil and 83 to 86% C_{10} acid.

In Germany, these results have led to extensive additional work, with the result that some *Cuphea* species are now grown in hectare quantities with excellent yields and evident agronomic potential (Zoebelein, H., private communication).

Liquid Wax Esters

Until the embargo on imports in 1972, sperm whale oil had been used extensively in the lubricant industry as the sole source for liquid wax esters. Annual consumption was in the order of 60 million lb. Although such esters could be prepared from vegetable oils through saponification, reduction of fatty acids to alcohols, and reesterification (48,49), the only other direct source for liquid wax esters appears to be the seed oil of jojoba (*Simmondsia chinensis* or *S. californicus*).

Jojoba grows wild in the deserts of southwestern United States and northern Mexico and has been the subject of much research during the past decade. Germplasm evaluation, agronomy, seed processing, and testing of finished oil products in lubricant applications have been carried out throughout the world (50-52). Jojoba nuts have been gathered from extensive wild stands, and plantations have been initiated. Although much research and development remains to be done, it appears at this point that jojoba is likely to become an economically successful new crop.

Other Unique Fatty Acids and Oils

Many seed oils contain high levels of other fatty acids that may be valuable as chemical intermediates. Also, plants are known to produce unique seed oils that differ greatly from the common triglyceride structure. These intact oils may have physical or chemical properties that make them desirable for utilization in specialized applications. Fatty acids, other than those described in this paper, include petroselenic acid (*cis*-6-octadecenoic acid), found in oil from *Foeniculum vulgare* and other seed oils of the Umbelliferae, and others with single unsaturation at uncommon locations, as well as acetylenic, allenic, and cyclic structures. In addition to the listed mono-, di-, and trihydroxy fatty acids and epoxy fatty acids, seed oils with keto groups are known to occur also. Combinations of many of the carbon-carbon and carbon-oxygen moieties in single fatty acids can be found in nature as well. The occurrence of unusual fatty acids has been reviewed in detail (53-55).

Some of the plants producing these fatty acids have been studied for their agronomic potential and appear promising. However, others even better suited might be found by further evaluation. Some intact seed oils contain high levels of special constituents, such as galactolipids in *Briza* species (56), acetoglycerides at 80 to 100% levels in *Celastrus, Euonymus,* and other species (57), estolide glycerides (tetra and penta acid glycerides) in *Lesquerella auriculata* and *Heliophila amplexicaulus* at 60 to 100% levels (58), cyanolipids at up to 65% in the seed oils of many species in the family Sapindaceae (59), and triterpenoids at 50% of the seed oil of *Carduus migrescens* (60).

Except for the *Briza* galactolipids, which have been evaluated successfully as an additive to improve loaf volume and crumb grain in protein-enriched breads (61), no attempts have been made to utilize any other of these unique lipids for food or industrial products.

DISCUSSION

The description presented above on the status of germplasm evaluation, agronomic testing, and product development shows that the concept of new crops for American agriculture and their utilization in food, feed, fiber, and other industrial applications is not new. USDA and cooperating agencies have actively pursued such a program for many years. However, it is only recently that economic and political factors have provided added stimulus. The need for more renewable resources in manufacturing and energy processes is a major factor in the increased interest. Other factors include our deteriorating trade balance and the dependence of farmers on traditional crops.

In this economic and political climate, one wonders why none of the described potentially new crops has been accepted. Analysis of past experience indicates that there are two major problems in development of new crops. The first problem is the need for coordination and timing of all facets of the research and development program for each crop. These facets include genetics, agronomy, plant physiology, harvesting, processing, product development, and by-product evaluation. Whenever one area of research is ahead of the others, a new crop may become available before outlets for the product have been established, or vice versa. A good example is the difference in the histories of crambe, and limnanthes, two sources for long chain fatty acids. For a long time product research on both crambe seed oil and meal were well ahead of the agronomic and genetic studies, whereas limnanthes has seen a vigorous approach to the problems of raising the crop, but little effort has gone into processing and product research. In both situations crop acceptance has been postponed.

The second problem is the difficulty experienced in breaking out of research into actual production. In private enterprise, whenever a research product appears ready for commercialization, funds may be made available from within the organization for plant facilities and marketing efforts. Commercialization of a new crop is complex, especially since the research is often carried out under the auspices of a government organization. The lack of seed supply for planting, the uneasiness of farmers to experiment with new crops without the prospects of a steady market, the unfamiliarity of seed processors with the parameters required for optimum oil and meal quality, the reluctance of chemical manufacturers to change raw material sources if supply cannot be guaranteed all contribute to the unlikelihood of breaking out of the proverbial vicious circle. One possible way out would be to establish a pilot production program for a few years, so that these problems can be solved without undue hardship on any one of the various cooperating sectors. This shortcoming has been recognized, and attempts are being made to develop demonstration programs that will bring some of the more promising new crops over this critical hurdle.

Ultimately, those chemical industries that see a future in the use of new crops as renewable sources for their feedstocks may change their operations to include participation in production of those crops. Such participation can be of differing degrees, depending on the crop as well as on the volume and quality of the final products desired. In some instances crops can be produced by simply contracting with farmers; in others more input, including total magement and control of the farming operations, may be required. It cannot be expected that these crops will be available in the free commodity market in the near future, as are major cash crops such as corn, wheat, soybeans, vegetables, and fruits. A desire and a concerted effort by the chemical industry and other interests to actively create these new crops, therefore, will be required.

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[Received January 12, 1979]