PRODUCTS FROM JOJOBA: A PROMISING NEW CROP FOR ARID LANDS

NATIONAL ACADEMY OF SCIENCES

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COMMITTEE ON JOJOBA UTILIZATION
Office of Chemistry and Chemical Technology
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1975

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Preface

In 1972 the Indian Division of the Office of Economic Opportunity (OEO) initiated activities that it hoped would lead to an industry based on the seed oil of the desert bush jojoba (*Simmondsia chinensis*). Such a new industry would improve the economies of Indian reservations in the southwestern desert regions of the United States.

In his letter of 22 August 1972 to Dr. Philip Handler, President of the National Academy of Sciences (NAS), Mr. Phillip V. Sanchez, the Director of OEO, requested a scientific and technical assessment, based on test results, of practical uses of jojoba oil. To study the problem, Dr. Handler appointed the Committee on Jojoba Utilization in the Office of Chemistry and Chemical Technology of the National Research Council (NRC).

In the summer of 1972, more than 87,000 pounds of jojoba seed were harvested by hand by Indians in Arizona and California. This difficult harvest provided a stockpile for full-scale testing of jojoba seed oil. The University of Arizona's Office of Arid Lands Studies and the University of California at Riverside directed the subsequent research. More than 75 corporations and research institutions, including some of the largest in the nation, were supplied with samples of the oil of up to 55 gallons for testing in products and processes.

The committee held a general meeting in Tucson, Arizona, on 29–30 March 1973; it met again in Washington, D.C., on 15 May 1973, and at Riverside, California, on 28–29 August 1974. At each meeting, researchers and industrial representatives informed the committee of their findings. Published documents on jojoba research and the large body of information reported at the First International Conference on Jojoba held in Tucson, Arizona, in June 1972 were also available to the committee.

At their final meeting, the committee members reviewed the knowledge available to them, drew up their conclusions, and drafted the present report. The report is not intended as a detailed technical analysis of jojoba products, but as a general survey that identifies what we know, highlights gaps in our knowledge, and makes suggestions for future actions. The report does not treat the botany or agronomy of jojoba in detail, nor does it cover questions of Indian economic development, arid-land ecology, or business strategies to develop jojoba as a crop. The Board on Agriculture and Renewable Resources of the NRC is initiating a follow-up study on the agricultural aspects of jojoba use that will include careful examination of agricultural economics and, probably, the economics of the initial stages of oil production and processing.

The committee gratefully acknowledges support of its efforts by the Department of Health, Education, and Welfare under contract number HEW-0S-74-21. Preparation of the report for printing by the NAS was administered by the Board on Agriculture and Renewable Resources of the NRC with the financial assistance of the Cooperative State Research Service of the Department of Agriculture.

The committee also wishes to thank Dr. Edward Haase and Prof. Demetrios Yermanos for making, respectively, the local arrangements for the meetings in Tucson and Riverside. Thanks are also due the contributors (see Appendix A) who shared their findings and opinions with the committee.

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Summary

The desert plant jojoba [*Simmondsia chinensis* (Link) Schneider] grows wild over an extensive arid area in the Sonoran Desert that covers parts of Arizona, California, and Mexico (see Figures 1 and 2). Estimates of the amount of seeds produced each year in jojoba's native habitat are over 100 million pounds. *The cultivation of jojoba, the manufacture of products from it, and the utilization of its by-products would greatly improve the economic situation of some native peoples and reservations in the area.*

Jojoba seeds (see Figure 3) contain about 50 percent by weight of a colorless, odorless oily liquid with unusual properties that is commonly referred to as "jojoba oil." The oil is chemically a liquid wax made up of nonglyceride esters having a narrow range of chemical composition; the esters are almost entirely composed of straight-chain acids and alcohols, each with 20 or 22 carbon atoms and 1 unsaturated bond. Jojoba oil is unique: an unsaturated, liquid wax that is readily extractable in large quantities from a plant source. Waxes of this type are difficult to synthesize commercially; the only other natural source is the sperm whale, an endangered species.

Waxes are used in many industries for a wide variety of applications in lubricants, paper coatings, polishes, electrical insulation,

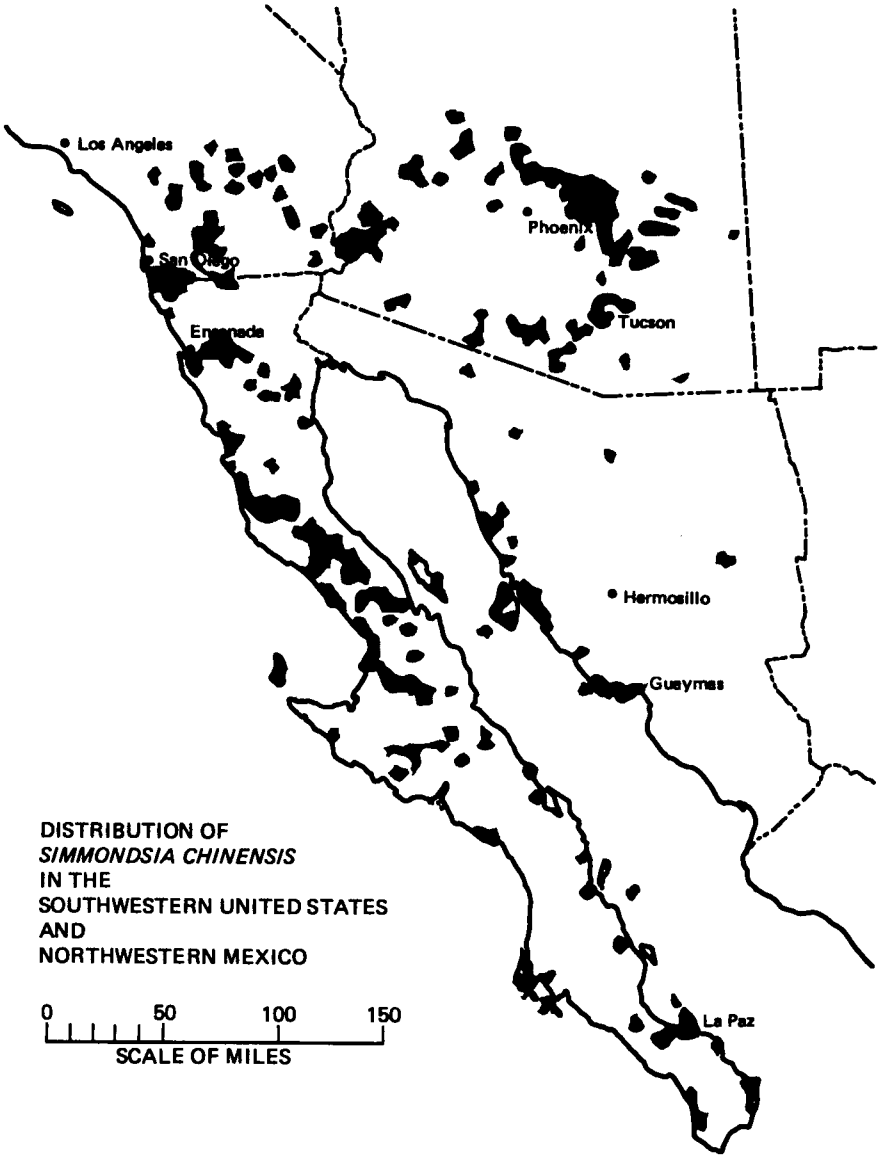

FIGURE 1 Distribution of *Simmondsia chinensis* in the Southwestern United States and Northwestern Mexico. (Map supplied by the Office of Arid Lands Studies, University of Arizona.)

carbon paper, textiles, leather, precision casting, and pharmaceuticals. *Jojoba oil is potentially useful for all these products.*

Liquid jojoba oil can be hydrogenated to a hard, colorless solid resembling spermaceti (a solid saturated form of sperm oil also obtained from sperm whales) carnauba wax, and beeswax in both chemical structure and properties. The completely hydrogenated wax has a high melting point, about 70 C. It is noteworthy that the price of natural and synthetic waxes has risen greatly in recent years; they now sell for record prices.

Substantial chemical research has been done on jojoba oil, much of it in the 1950s by the U.S. Department of Agriculture. A 1974 publication by W. C. Sherbrooke and E. F. Haase (see Appendix B) lists 256 references to the plant and its products. Though much is known about the physical and chemical nature of jojoba, industrial development is just beginning.

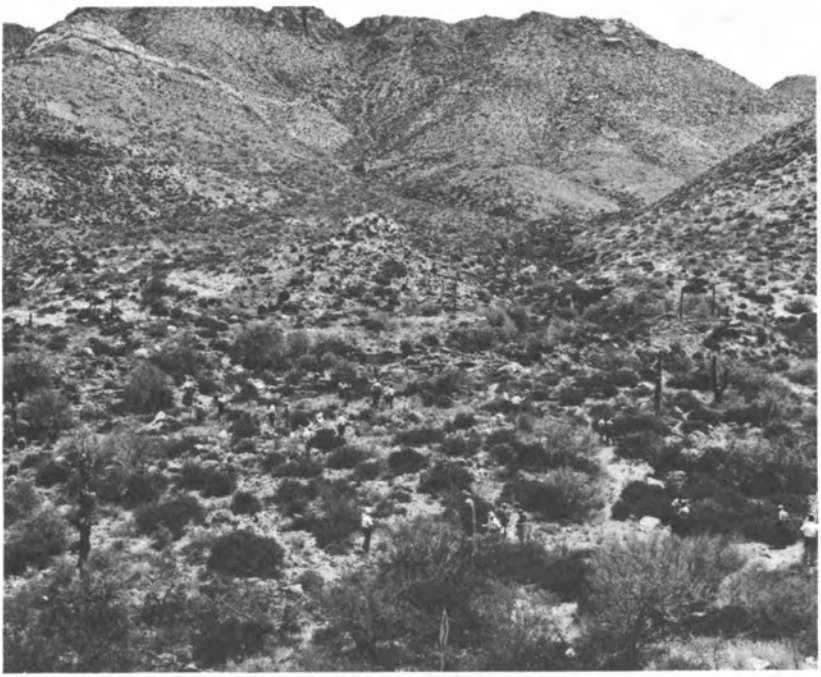

FIGURE 2 Jojoba bushes covering the hillslopes in the Sonoran Desert near Tucson, Arizona. (Photo courtesy of the Office of Arid Lands Studies, University of Arizona.)

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FIGURE 3 Jojoba seeds. (Photo courtesy of Noel D. Vietmeyer.)

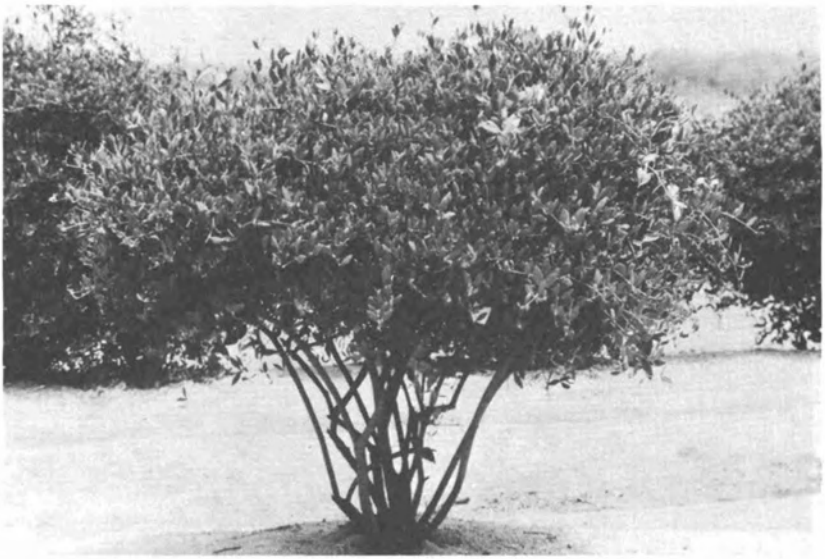

FIGURE 4 Jojoba bush, pruned for easy harvest. (Photo courtesy of Noel D. Vietmeyer.)

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In 1974, 35 acres of jojoba plantation were established on Indian lands in southern California, and two Indian jojoba cooperatives were formed in California and Arizona.

The jojoba plant, although usually bushy, may grow 10 feet high, offering a thick cover in the desert (see Figure 4). Its natural life span appears to be more than 100 years, perhaps more than 200. A nontoxic plant, it is browsed by cattle, sheep, and goats. Jojoba is dioecious: Pollen is produced on "male" plants; the "female" plants bear the seeds, which are about the size of peanuts.

Jojoba is native to the Sonoran Desert of Mexico and the United States, where it occupies elevations between 2,000 and 4,000 feet, rarely occurring lower (it occurs down to sea level along the outer coast of Baja California). Jojoba is usually restricted to well-drained, coarse desert soils and coarse mixtures of gravels and clays (H. S. Gentry: see Appendix B). The plant has shown the ability to develop without additional water in an area with an annual rainfall of 8 inches. Although it does occur in areas where the rainfall is less than 5 inches a year, it is most prevalent where the rainfall is 15–18 inches a year.

Mature plants in the United States are known to yield as much as 12 pounds of seeds (dry weight) and more; jojoba does not appear to be subject to serious insect or disease damage.

CONCLUSION 1
The Commercial Potentials for Jojoba Products

THE COMMITTEE CONCLUDES UNANIMOUSLY THAT JOJOBA OIL AND ITS HYDROGENATED PRODUCT HAVE MARKETABLE PROPERTIES.

There is a sound technical basis on which to move forward in establishing jojoba-based industries. For the United States the jojoba plant could become an important national materials resource, each year providing a supply of oil and wax for the nation's industries.

Jojoba oil is a new product with numerous important potential applications, but *its development can reliably rest on its ability to substitute for existing oils and waxes such as sperm oil, carnauba wax, beeswax, and spermaceti.*

The wax-ester structure of jojoba oil is not easily synthesized in commercial quantities, nor is it readily available from any other natural source, except the sperm whale. The possibility of displacement by synthetics appears remote.

Preliminary experiments at the University of California at River-

side and in Israel demonstrate that jojoba plants can be cultivated and their yield greatly improved over that of plants in the wild. Under cultivation, an average annual yield of 5 pounds of clean, dry seeds can be obtained from a mature bush; a plantation could yield 1,000 to 2,000 pounds of oil per acre per year. Start-up costs, if irrigation water is available, are estimated to be $1,500 per acre on average agricultural land and as high as $2,800 per acre in rough desert terrain; but plantation maintenance costs, including harvesting, would be only about $100 per acre per year. From the current price of sperm oil (40¢ per pound) and of carnauba wax ($2 per pound), it can be seen that returns per acre from established jojoba plantations would be substantial.

CONCLUSION 2
Jojoba and Sperm Oil

JOJOBA OIL RESEMBLES SPERM OIL IN CHEMICAL COMPOSITION AND PHYSICAL BEHAVIOR; IF A SUFFICIENT SUPPLY OF JOJOBA OIL WERE AVAILABLE AT A COMPETITIVE PRICE, IT WOULD BE USED AS A SUBSTITUTE FOR SPERM OIL.

The structural similarity of jojoba oil and sperm oil is indicated by an identity of chemical-compound type (wax esters as opposed to the glycerides of other natural oils and fats), almost identical unsaturation (number of double bonds) in both the acid and the alcohol portions of the wax esters, and similar molecular chain lengths. Evidence presented to the committee has shown conclusively that *jojoba oil can duplicate sperm oil performance as a high-pressure lubricant.* As this is the major use for sperm oil, it is strong evidence that, technically, jojoba is a marketable commodity.

In the past, sperm oil found extensive use in United States industry as a lubricant in automotive and tractor transmission fluids, in metal-working oils, and for gears and other machine parts requiring extreme-pressure properties. In all these applications, jojoba oil has the needed characteristics to replace sperm oil practically on a one-to-one basis.

In December 1970, under provisions of the Endangered Species Conservation Act, the United States banned import of oil, meat, and other products from whales. Yet sperm oil was at that time considered to be of crucial importance to the nation; until recently, sperm oil was stockpiled against national emergencies. Sperm-oil consumption in the United States averaged about 50 to 55 million pounds per

year in the late 1960s; about half was used in lubricants, particularly for extreme-pressure conditions.

The sperm-oil import ban has spawned several sperm-oil substitutes: selectively formulated lard oil or petroleum products with proprietary additives to meet the requirements of specific uses. In comparison with these formulated substitutes, jojoba is a virtual sperm-oil *duplicate—a material that is so close in chemical structure that it can probably be used as a sperm-oil substitute for the complete range of uses, without requiring major reformulations.*

Chemically, jojoba oil has industrial advantages over sperm oil:

- It is more than 97 percent wax esters. It contains no glycerides, very little (1 percent) free acid or alcohol, and almost no hydrocarbons, steroids, or other contaminants. Sperm oil, on the other hand, contains considerable amounts of glycerides (sometimes over 20 percent) and often free acid as well.
- Jojoba oil has almost no odor.

The carbon-chain lengths in jojoba are strikingly uniform. Carbon chains 20 and 22 atoms long make up about 93 percent of the acids and alcohols in the wax esters. In sperm oil the carbon chains are much more variable.

CONCLUSION 3
Hydrogenated Jojoba Oil

ONE JOJOBA PRODUCT THAT HAS AN IMMEDIATE MARKET POTENTIAL IS HYDROGENATED JOJOBA OIL.

This hard, white, semicrystalline wax has chemical structure and properties very like those of carnauba wax. These properties seem to assure it a future role in industry. Carnauba wax comes from Brazil, where it is laboriously scraped from the fronds of palm trees. In recent years, the supply has fluctuated greatly and decreased generally. With rising labor and transportation costs, it is becoming a high-priced item: The highest grades sold at over $2 per pound in 1974. Other waxes with carnauba-like properties (candelilla, beeswax, spermaceti) are also drastically rising in price and fluctuating in supply.

If hydrogenated jojoba oil could be developed into a domestic wax

source, immune from the vagaries of international commerce, U.S. industry would be assured of a continuous supply of uniform quality.

CONCLUSION 4
Indian Economic Development

JOJOBA COULD BECOME THE BASIS FOR VIABLE INDIAN-OWNED AND INDIAN-OPERATED INDUSTRIES; THE DEVELOPMENT OF JOJOBA-BASED FARMING AND INDUSTRY WOULD PROVIDE CONSIDERABLE ECONOMIC AND SOCIAL BENEFITS TO INDIAN RESERVATIONS IN ARIZONA AND CALIFORNIA.

Indians of the Sonoran Desert are among the most impoverished people in the United States. Unemployment is widespread on the reservations, and welfare rolls are long. There are few economic incentives to remain on the reservation. A jojoba-based industry would allow Indians to help themselves toward economic self-sufficiency by using local labor to grow and process jojoba. *It is estimated that 17 reservations in California and 9 in Arizona could grow jojoba.*

CONCLUSION 5
Jojoba for Improving the Productivity of Arid Lands

JOJOBA CAN INCREASE THE PRODUCTIVITY OF ARID LANDS NOT SUITABLE FOR CONVENTIONAL CROPS.

The jojoba plant tolerates extreme desert temperatures; daily summer highs of 110–115 F in the shade are common in its habitat. According to the literature, 12 inches of rainfall a year are enough to support large stands of productive jojoba bushes. Jojoba would levy only a small strain on water supplies, which are now so heavily taxed (by population growth and water-demanding crops such as cotton and sorghum) that water tables are dangerously threatened. A true drought-resistant desert shrub, jojoba grows well under marginal soil and moisture conditions.

Perhaps jojoba's greatest attribute for arid lands is that it requires little or no water during the summer. To produce new growth, set flowers, and produce seeds, jojoba needs moisture during the winter and spring. From the time the seeds are formed in the late spring, moisture is unnecessary. This schedule fits well with the arid environment; water is needed when it is most available and not needed when it is scarce. This schedule contrasts with most other crops, which sur-

vive drought only if they receive moisture during the hottest and driest months.

Jojoba also seems very tolerant of saline and alkaline soils and saline irrigation water—the cause of barrenness in many arid areas. With careful management, jojoba may be able to make these areas productive.

CONCLUSION 6
Next Steps

THE COMMITTEE BELIEVES STRONGLY THAT THE HEW-SPONSORED PROGRAMS SHOULD BE CONTINUED, EVEN DRASTICALLY EXPANDED, TO GIVE INDIANS IN ARIZONA AND SOUTHERN CALIFORNIA JOJOBA-BASED INDUSTRIES THAT ARE WITHIN THEIR CAPACITY TO CONTROL, OPERATE, AND MANAGE.

The country's need for extreme-pressure lubricants, for renewable resources, and for Indian economic development would be alleviated if jojoba were developed into a crop plant.

Research and development should now be committed to the jojoba oil supply problem. The committee is convinced of the value of jojoba products. To produce them in quantity is now the challenge. Natural stands cover large areas of the southwestern United States and of Mexico, but the vagaries of weather and the remote, steep terrain, unkempt bushes, and extreme heat during harvest time make it uneconomic to exploit them. *The future of jojoba lies in developing it into a cultivated crop.*

That the plant responds favorably to cultivation is known. Already, small plantations have been established in southern California (35 acres on the Barona Indian Reservation, 5 acres at the University of California) and in Israel (10 acres at the Ben Gurion University of the Negev). These efforts should be expanded and new plantations initiated.

Increased investment is needed because jojoba plants do not bear harvestable quantities of seed for 5 years. This long time required for the plantation to reach maturity, coupled with the present lack of established markets, makes cultivation a commercially risky proposition. *The committee believes that this unique agricultural product is well worth subsidizing. They expect that the product can ultimately become self-supporting.* The fact that impoverished Indian tribes occupy the regions where jojoba is indigenous is a compelling argument for further governmental support of such a project.

Plans should begin immediately for starting 2,000 acres of plantation, to be developed over 5 years by establishing 400 acres per year. This long-range program will call for the expenditure of several million dollars over the 5 years and could include a program to train Indians to develop and maintain the plantation and to produce and market the products. After 5 years the plantations should become self-supporting and provide a source of income from the sale of the oil.

The acceptance of any natural product is limited by availability of an assured supply: No one will be willing or able to begin marketing (or ordering) the material until an ample, stable supply is being produced. This consideration is another important reason for starting plantations.

CONCLUSION 7
Limitations and Research Needs

Jojoba production suffers from three constraints: (1) newly planted seedlings require 5 years before they bear adequate amounts of seed for commercialization; (2) there has been little agronomic selection; and (3) the available seed produces highly variable plants. Though the average is 5 pounds of seed per bush, some yield 12 pounds, others 1.5 pounds. We are unable to distinguish between male and female seeds, so that several seeds must be wastefully planted at each plant site to ensure that the desired sex is obtained.

Research is needed to overcome each of these limitations. Success in any one will ease and quicken the development of the plant as a commercial crop.

Although research is needed most in the agronomic aspects of jojoba production, the committee has noted a number of promising areas for productive chemical research:

- Knowledge of jojoba oil is based on experiments with the naturally occurring oil, which has *cis* double bonds. Recent work has shown that catalysis gives almost instantaneous isomerization to a mixture in which the *trans* double bond predominates 4 : 1. This mixture has been virtually unstudied.
- Addition of sulfur chloride to the double bonds of jojoba oil produces Factices ranging from viscous liquids to rubbery solids. An array of products awaits industrial testing and analysis.
- Partial hydrogenation of jojoba oil (instead of complete hydro-

genation) produces a range of soft waxes, possibly with important industrial properties.

- Combinations of hydrogenated jojoba oil with paraffin, with polyethylene, and with carnauba wax also provide products with different properties, many of which may be commercially important.

Scientific Background

JOJOBA OIL

In chemical structure, jojoba seed oil is not a fat but a liquid wax. Fats, including the seed oils of all other plants, are triglycerides (a molecule of glycerol esterified with three molecules of fatty acids). Waxes like jojoba and sperm oil are wax esters (one molecule of a long-chain alcohol esterified with one molecule of a long-chain fatty acid). Jojoba oil is unique among vegetable oils, as sperm oil is unique among animal oils.

The jojoba plant is apparently the result of an evolution that produced a plant with its own enzymes and biosynthetic pathways that produce the oil. Such a vegetable oil has never before been available to industry. It seems likely that in the current programs, making jojoba oil available for the first time, industrial chemists will soon uncover many uses.

The following general characteristics should make jojoba oil valuable:

- its natural purity and molecular simplicity
- its stability: it is a nondrying oil, having such high resistance to oxidation that it can be stored for years without becoming rancid
- its lubricity after sulfurization
- its source of chemicals with 20 and 22 carbon atoms
- its unsaturation (double bonds)

The wax and protein content of seeds from 20 bushes are shown in Table 1. Most jojoba seeds are between 45 and 60 percent oil, and the average is close to 50 percent. The clear, unsaturated oil can be obtained by the pressing or solvent-extraction methods used commercially to isolate vegetable oils from cottonseeds, soybeans, coconuts, and corn.

Jojoba oil from plants throughout California and Arizona has the same wax-ester composition. The acids and alcohols that make up these esters do not vary appreciably with location, soil type, rainfall, or altitude. The oil of a rare prostrate variety of jojoba that grows only along the Pacific coast of Baja California differs slightly from that of the more common variety of jojoba in that it contains a larger proportion of the higher homologs. (Information supplied by T. K. Miwa. Also see Selected Readings in Appendix B.)

The oil does not change in composition as the seed matures, nor does it change during storage. Seeds analyzed 25 years after harvest show no change in oil–ester composition. Thus seeds (if dried) can be stored without deterioration or chemical change. (Information supplied by T. K. Miwa.)

Tests to determine the quantity and quality of oil from seeds harvested before maturation indicate that jojoba oil in green seeds has exactly the same chemical composition as that in the mature seeds. (Information supplied by T. K. Miwa.) Green seeds contain the same amount of oil as mature seeds, but also contain moisture. As

TABLE 1 Wax and Protein Content of Seeds from Individual Jojoba Plants

Seed Sample (High Wax %)	Wax %	Protein %	Seed Sample (Low Wax %)	Wax %	Protein %
1	56.9	27.7	11	49.1	27.7
2	56.4	26.6	12	45.8	31.2
3	56.4	27.3	13	45.5	29.7
4	57.9	26.3	14	48.6	32.0
5	56.9	27.5	15	46.8	29.8
6	58.6	32.0	16	43.2	33.4
7	56.9	28.7	17	45.4	30.8
8	56.8	28.4	18	47.5	29.6
9	56.5	30.5	19	47.7	30.8
10	56.7	30.3	20	47.5	29.6
Mean	57.0	28.5	Mean	46.7	30.7

Source: D. M. Yermanos.

they mature on the bushes, there does not appear to be an absolute increase in the quantity of oil, just a decrease in moisture.

Chemical Structure

Jojoba oil is composed entirely of esters of high molecular weight, straight-chain mono-ethylenic acids and mono-ethylenic alcohols. The unsaturated acids are a mixture of eicosanoic (C_{20}) and docosanoic (C_{22}), with small quantities of palmitoleic (C_{18}) and oleic (C_{16}) acids. The unsaturated alcohols are a mixture of eicosanol and docosanol, with smaller quantities of hexacosanol and alcohols of lower molecular weight.

Jojoba oil is chemically purer than most natural substances; after simple refining (filtration through fuller's earth), it contains no resins, tars, alkaloids, or glycerides—and only traces of saturated wax, steroids, tocopherols, and hydrocarbons. (Information supplied by T. K. Miwa.) Yellow vegetable pigment can be removed with bleaching earth. The oil also has an unusually narrow range of wax-ester structures—over 85 percent of the esters present are combinations of C_{20} and C_{22} acids and alcohols (see Table 2).

The double bonds in natural jojoba oil have *cis* stereochemistry.

TABLE 2 Gas-Chromatographic Composition of Expeller-Pressed Jojoba Oil

Wax esters	%	Free alcohols	%		%
C-33	0.02	C-16	0.01	Campesterol	0.05
C-34	0.08	C-18	0.04	Stigmasterol	0.08
C-35	0.04	C-20	0.49	Sitosterol	0.21
C-36	1.16	C-22	0.49	Others	0.52
C-37	0.02	C-24	0.07		
C-38	6.23	C-26	0.01		
C-39	0.04		1.11		
C-40	30.56				
C-41	0.10	Free acids	%		
C-42	49.50	C-16	0.08		
C-43	0.06	C-18	0.23		
C-44	8.12	C-19	0.01		
C-45	0.03	C-20	0.60		
C-46	0.86	C-21	0.03		
C-48	0.16	C-22	0.03		
C-50	0.06	C-24	0.02		
	97.05		1.00		

Source: T. K. Miwa.

Isomerization with nitrous oxide and other such reagents produces an equilibrium mixture with 80 percent *trans* and 20 percent *cis* double bonds. In contrast to the clear, liquid natural oil, this isomerized product is a thick opaque cream resembling face cream. (Information supplied by J. Wisniak.) Many possible uses of this product remain to be explored.

The conventional position for a double bond in a natural fat or oil is Δ^9 (i.e., between carbon 9 and carbon 10 on each of the fatty acids), but jojoba oil has mainly Δ^{11} and Δ^{13} alcohols and acids, though some Δ^9 acid is present (see Table 3).

Physical Properties

Jojoba oil is soluble in common organic solvents such as benzene, petroleum ether, chloroform, carbon tetrachloride, and carbon disulfide, but it is immiscible with alcohol and acetone.

TABLE 3 Alcohol/Acid Structures of Jojoba Oil Determined by Gas Chromatography and Mass Spectrometry

Carbons and Double Bonds	Alcohol	Percent	Carbons and Double Bonds	Acids	Percent
14:0	Tetradecanol	trace	12:0	Dodecanoic	trace
16:0	Hexadecanol	0.1	14:0	Tetradecanoic	tr.
17:1	Heptadec-8-enol	tr.	15:0	Pentadecanoic	tr.
18:0	Octadecanol	0.2	16:0	Hexadecanoic	1.2
18:1	Octadec-9-enol	0.7	16:1	Hexadec-9-enoic	0.2
18:1	Octadec-11-enol	0.4	16:1	Hexadec-7-enoic	0.1
20:0	Eicosanol	tr.	17:1	Heptadecenoic	tr.
20:1	Eicos-11-enol	43.8	18:0	Octadecanoic	0.1
21:1	Hencos-12-enol	tr.	18:1	Octadec-9-enoic	10.1
22:0	Docosanol	1.0	18:1	Octadec-11-enoic	1.1
22:1	Docos-13-enol	44.9	18:2	Octadecadienoic	0.1
24:1	Tetracos-15-enol	8.9	18:3	Octadecatrienoic	tr.
			19:1	Nonadecenoic	tr.
			20:0	Eicosanoic	0.1
			20:1	Eicos-11-enoic	71.3
			20:2	Eicosadienoic	tr.
			22:0	Docosanoic	0.2
			22:1	Docos-13-enoic	13.6
			23:1	Tricosenoic	tr.
			24:0	Tetracosanoic	tr.
			24:1	Tetracos-15-enoic	1.3

Source: G. F. Spencer and T. K. Miwa.

TABLE 4 Properties of Jojoba Oil[a]

Freezing point	10.6–7.0 C	Iodine value	82
Melting point	6.8–7.0 C	Saponification value	92
Boiling point at 757 mm under N_2	398 C	Acid value	2
Smoke point (AOCS Cc 9a-48)[b]	195 C	Acetyl value	2
Flash point (AOCS Cc 9a-48)[b]	295 C	Unsaponifiable matter	51%
Fire point (COC)	338 C	Total acids	52%
Heat of fusion by differential scanning calorimetry	21 cal/g	Iodine value of alcohols	77
Refractive index at 25 C	1.4650	Iodine value of acids	76
Specific gravity, 25/25 C	0.863	Average molecular weight of wax esters	606
Viscosity			
Rotovisco (25 C)			
MV-1 rotor in MV cup	35 cp		
Plate and cone with Pk-1	33 cp		
Brookfield, spindle #1, 25 C	37 cp		
Cannon-Fenske, 25 C	50 cp		
Cannon-Fenske, 100 C	27 centistokes		
Saybolt, 100 F	127 SUS[c]		
Saybolt, 210 C	48 SUS[c]		

[a]Oil from expeller-pressed jojoba seeds starts to freeze at 10.6 C (51 F). It solidifies into a thick paste at 7 C. Frozen oil, allowed to warm up, melts at 7 C (45 F).
[b]Smoke and flash points determined according to the official method, Cc 9a-48, of the American Oil Chemists' Society.
[c]Saybolt Universal seconds.

Some detailed properties are listed in Table 4.

The oil's high viscosity index, high flash and fire points, high dielectric constant, and high purity are key properties favorable for select industrial uses.

Jojoba Oil as a Lubricant

Jojoba oil may be made to react with sulfur to yield a stable product containing a relatively large amount of sulfur, which *could* serve well as a lubricant or as a lubricant additive.

Sperm oil is widely used in lubricants because of the oiliness and metallic wetting properties it imparts and its nondrying characteristics that prevent gumming and tackiness. The composition and physical properties of jojoba are close enough to sperm oil to suggest the use of jojoba oil as a substitute for most of the uses of sperm oil (see Table 4).

Jojoba oil has several advantages over the similar product from the sperm whale:

- it has a n.ild, pleasant odor
- it contains no glycerides and very little besides the liquid wax
- it requires little or no refining to prepare it for most lubrication purposes
- it is a vegetable product that can be produced in many resource-poor countries

Sperm oil has been used as an extreme-pressure and antiwear additive in lubricants for gears in differentials and transmissions, in hydraulic fluids that need a low coefficient of friction, and in cutting and drawing oils. In some of these, sperm oil has been used directly, but it is usually sulfurized (sometimes epoxidized, chlorinated, or fluorinated). Gear lubricants (e.g., in automobile transmissions) commonly contain 5 to 25 percent of sulfurized sperm oil.

Experiments have been conducted on jojoba oil to test (using Four-Ball Extreme Pressure and Falex machines) whether it has lubricating and antiwear properties comparable to those of sperm oil (Gisser, personal communication, 1974). On the basis of the performance evaluations already conducted, sulfurized jojoba oil shows properties equivalent to sulfurized sperm oil in lubricant applications. (The accuracy of these results has been substantiated by H. Gisser.) The characteristics of sulfurized jojoba oil are remarkably similar to those of sulfurized sperm oil (see Table 5). The sulfurized jojoba and sulfurized sperm oils are essentially equivalent in improving the load-carrying capacity under extreme-pressure conditions of both naph-

TABLE 5 Characteristics of Sulfurized Jojoba and Sperm Oils

Test	Sulfurized Jojoba Oil	Sulfurized Sperm Oil
Sulfur, percent	9.88	9.98
Viscosity, at 37.8 C	3,518 SUS[a]	1,961 SUS[a]
Viscosity, at 99 C	491 SUS[a]	201 SUS[a]
Specific gravity at 15.6 C	0.9476	0.9613
API at 15.6 C	17.82	15.71
Flash point	250 C	243 C
Fire point	282 C	280 C
Free fatty acids (oleic)	1.55	2.35
Saponification no.	162	195
Pour point	16.1 C	15.6 C
Corrosion, 90/10, 3 h at 100 C	2A	2A
Color, API, 10% in 1¾ color oil	4¾	8+

Source: H. Gisser.
[a]Saybolt Universal seconds.

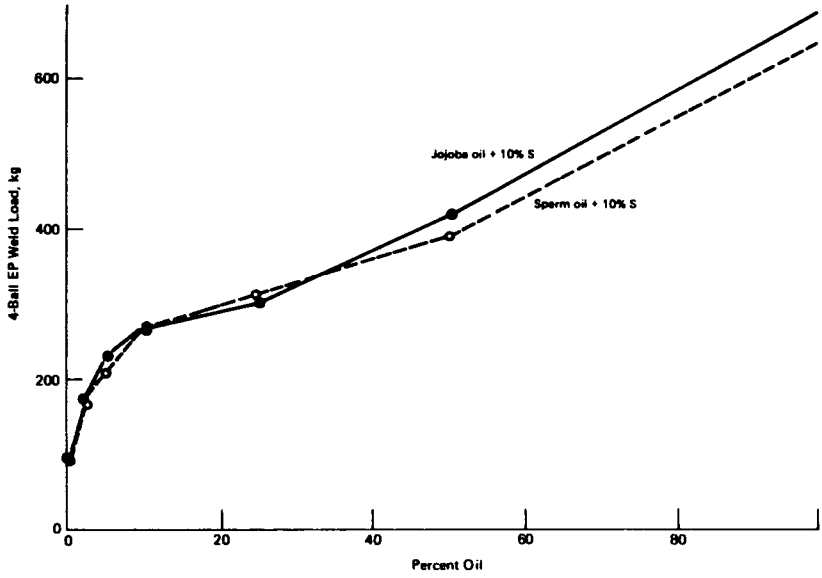

FIGURE 5 Sulfurized oil in naphthenic oil.

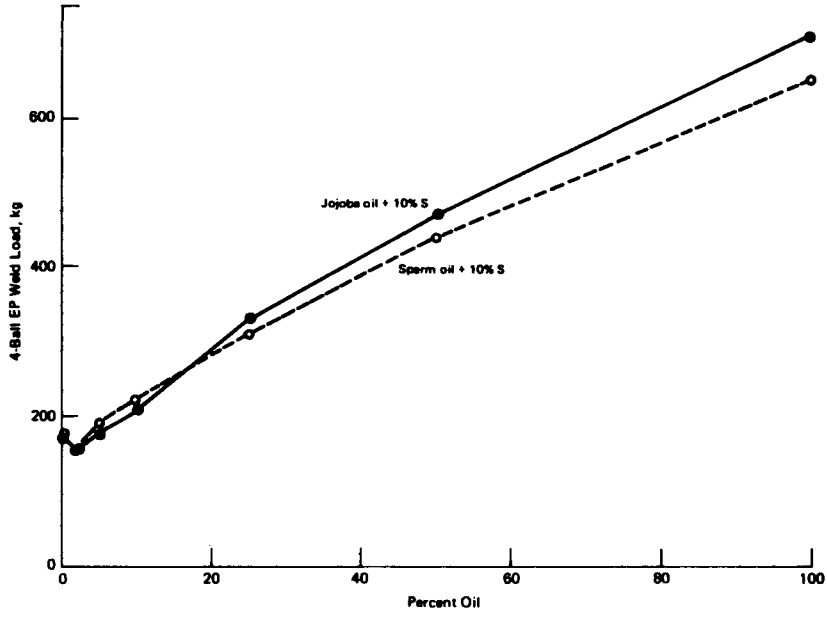

FIGURE 6 Sulfurized oil in bright stock oil.

thenic and bright stock base oils. They exhibit approximately equivalent extreme-pressure (EP) properties when tested neat. Small amounts of sulfurized jojoba and sulfurized sperm oils are also equally effective antiwear additives to the naphthenic and bright stock oils (see Figures 5 and 6).

Tests on sulfurized jojoba oil as a component in a lubricant composition for typical shop metal-cutting operations are in progress, and laboratory tests are being conducted. Figure 7 shows the markedly improved performance of both sulfurized jojoba and sperm oils as compared with that of base mineral oils, as well as the comparable performance characteristics of jojoba and sperm products.

Jojoba Oil as a Source of Acids and Alcohols

Jojoba seed oil could become a source of straight-chain mono-unsaturated alcohols and acids. There are no other readily available sources for these acids and alcohols, and in jojoba oil they are present in relatively high concentrations. They can be isolated almost uncontaminated by any impurity. These compounds could be used as intermediates in the preparation of numerous other compounds—disin-

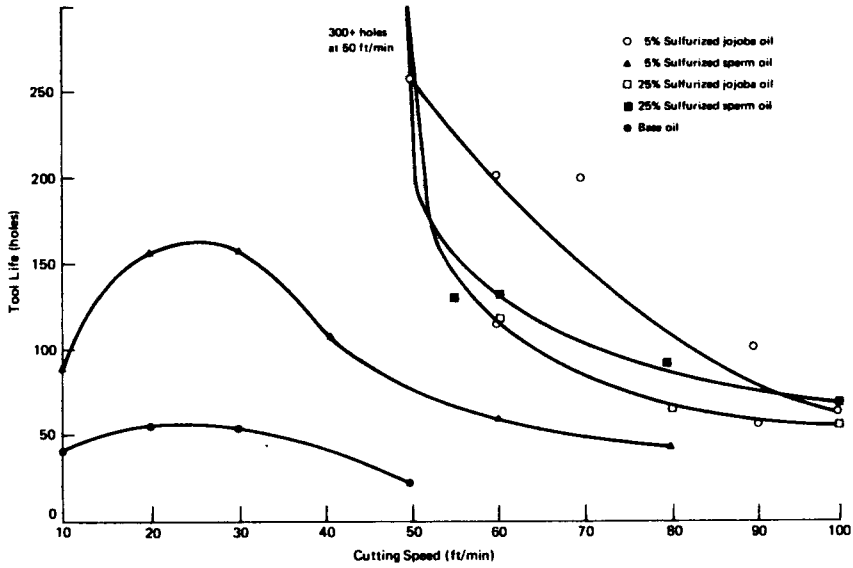

FIGURE 7 Relationship between tapping tool life and cutting speed. (Source: J. Messina.)

fectants, surfactants, detergents, lubricants, driers, emulsifiers, resins, plasticizers, protective coatings, fibers, corrosion inhibitors, bases for creams and ointments, antifoamers, and other products. Long-chain unsaturated alcohols have been prepared by sodium reduction of jojoba oil (Molaisin *et al.*, 1959; see Appendix B).

Miscellaneous Uses

Jojoba's antioxidation characteristics, which give it high resistance to rancidity, suggest that field uses requiring a stable vegetable oil may prove an important market for jojoba oil. Possibilities that come to mind include using it as a carrier for pesticides and plant hormones, as a water-evaporation retardant, for sizings and waterproofing, and for softening leather, paints, and adhesives.

Jojoba oil reacts with sulfur chloride to form compounds with a wide range of properties, from oils to rubbery solids known as Factices. Varnishes, rubber, adhesives, and linoleum can be produced from such preparations (Ellis, 1936; Spadaro and Lambou, 1973; see Appendix B). A patent covers the use of jojoba Factice in the manufacture of printing ink (Whitner, 1949; see Appendix B). The array of Factices with widely different viscosities that can be produced offers a wide open field for research and product development.

Although this report does not consider uses for jojoba oil in food, it is worth noting that its different chemical structure may make it resistant to hydrolysis by lipases, the digestive enzymes that hydrolyze fats. A great deal of expensive research would be needed for proof and acceptance, but this property might eventually lead to its use in low-calorie fatty foods and as masks to protect ingested materials from acid and enzymic degradation in the stomach.

Its resistance to rancidity and several other properties are promising for its use in cosmetics. Although initial skin-sensitivity testing looks promising, much expensive research still remains to be done.

Polyethylene dissolves readily in hot jojoba oil. The jojoba becomes microencapsulated and, over a period of days, oozes out. The residual polyethylene shows no sign of the jojoba oil. (Information supplied by T. K. Miwa.) This appears to be a fruitful area for research and product development.

HYDROGENATED JOJOBA OIL

Jojoba oil can be hydrogenated to a hard white wax. The catalysts and conditions used to hydrogenate vegetable oils to margarine or

shortening can be used to make a sparkling white semicrystalline material. A hard product with a high melting point, it has properties competitive with beeswax and candelilla, carnauba, and spermaceti waxes. Solid jojoba wax is not yet available in quantities suitable for industrial purposes, but the other waxes are subject to steeply rising costs and uncertainties of supply: Candelilla and carnauba are imported into the United States; imports of spermaceti have recently been banned because of the endangered status of sperm whales. So hydrogenated jojoba oil appears to have considerable commercial promise. Virtually 100 percent wax esters, hydrogenated jojoba oil is made up of saturated C_{20} and C_{22} fatty acids esterified with saturated C_{20} and C_{22} fatty alcohols–no triglycerides are present. X-ray diffraction has shown that the ester molecules are lined up in hexagonal arrays, but the samples are paracrystalline rather than completely crystalline, probably because slightly differing carbon-chain lengths prohibit perfect ordering. (Information supplied by T. K. Miwa.)

Hydrogenated jojoba oil has a lower melting point and is softer than carnauba (the "king of waxes"); nevertheless, it has several properties, such as purity, whiteness, and crystallinity, that may make it competitive in many applications. Where crystallinity is a disadvantage, hydrogenated jojoba oil can easily be made amorphous (like carnauba) by adding small amounts of other waxes or polyethylene.

Furthermore, hydrogenated jojoba oil is produced from the liquid unsaturated oil, which is more readily purified than a solid, natural wax such as carnauba. Jojoba oil's double bonds offer chemical functionality that can be capitalized on to produce partially hydrogenated jojoba oil, which offers exciting possibilities for industry because an array of soft white waxes and creams can be produced at will. Thus, the jojoba product is structurally modifiable, whereas the saturated waxes are not.

Hydrogenated jojoba oil is miscible with paraffin, glycerides, and polyethylene. It appears to be broadly useful for upgrading cheap waxes such as paraffin wax. Its combinations with polyethylene reportedly offer an array of blends with a wide range of properties and potential uses. (Information supplied by T. K. Miwa.)

Jojoba oil hydrogenates readily under mild conditions (for example, 3 g of Girdler Catalyst G-53 per liter of oil, 90–100 C, 100–200 psi hydrogenates the material completely in 15–30 minutes). (Information supplied by J. Wisniak.) Steam sparging removes hydrogenation odor. The costs of hydrogenation to convert the oil into a solid

wax in larger-scale commercial operations is expected to be in the range of $0.04–0.10 per pound.

Melting Point and Hardness

The fully hydrogenated wax has a melting point of about 70 C (158 F). It is also very hard, approaching the hardness of carnauba wax. Comparison of its hardness with that of other waxes is shown in Table 6.

TABLE 6 Hardness of Hydrogenated Jojoba Wax and Several Other Vegetable Waxes

Wax	Hardness[a]
Hydrogenated jojoba oil	1.9
Carnauba wax	2.6
Cane wax	2.1
Beeswax	0.38
Paraffin	0.24

Source: T. K. Miwa.
[a]Brinel Hardness Number at 25 C, 4.3 kg load for 60 sec on 10.0-mm diameter steel ball.

Uses

The main uses for saturated waxes are in floor finishes, carbon paper, and polishes for furniture, shoes, and automobiles. They are also widely used to raise the melting point, gloss, and hardness of other waxes for use in paper, textiles, insulating materials, batteries, candles, matches, soap, salves, chalk, and crayons. Waxes are used for film coatings in the food industry to retard shrinkage, reduce spoilage, minimize aging, and retain flavor. In the United States, fruits, vegetables, and chocolate confections are also treated in this way. Hydrogenated sperm oil (spermaceti) and other waxes are used as release agents and lubricants in bakeries and as coatings, masks, and sizings in nonfood products. Hydrogenated jojoba oil appears to have commercial potential for many of these uses.

Probably, hydrogenated jojoba oil's most outstanding and valuable characteristic is its hardness. This should make it useful in polishes and the hard ink coatings required for carbon paper and similar products.

Emulsifiability with water for self-lustering floor polishes and aqueous creams for pharmaceutical products and furniture polishes also is a highly valued property of some waxes. A 30 percent wax-in-water emulsion has been prepared from hydrogenated jojoba wax using 4 percent stearic acid and 2 percent triethanolamine as emulsifying agents. The wax emulsified easily, and the prepared emulsion after more than 1 month shows no sign of water separation—an indication of good stability. This good stability, combined with the excellent hardness of the hydrogenated product, should enhance its desirability for emulsions in a variety of applications.

Hydrogenated jojoba oil has important potentials in candlemaking industries. It is combustible and smokeless and has a low ash content. The pure wax makes a brittle, unsatisfactory candle, but it blends with other waxes or with 1 percent polyethylene to produce a high-quality product. Its melting point is high enough to produce candles that do not readily melt or drip around the edges or melt during storage in warm climates. A particular use might be in dipped candles with a layer of hydrogenated jojoba oil deposited on the outside of softer waxes or fats to support them and prevent sagging and dripping. The market for beeswax–jojoba and paraffin–jojoba candles, in particular, appears promising.

Plastic flow is an important property for high-gloss buffing waxes and in high-pressure lubricants. Hydrogenated jojoba oil buffs satisfactorily and leaves a coat hard enough for use in both solvent- and emulsion-type floor waxes. Some initial tests suggest that hydrogenated jojoba oil has industrial potential in solvent-type waxes, especially in self-polishing wax formulations. But one test indicates that jojoba wax is unsatisfactory for paste or liquid formulation or in carbon-paper inks because it crystallizes to a dry powder from an oil or solvent without swelling (because of poor solvent retention). It could, however, be used as a blend with petroleum waxes, which tend to form gels instead of lattice crystals with solvents.

If wax is to be used for insulators, a high dielectric constant is an important property, and hydrogenated jojoba oil has it. Because of of its crystallinity, hydrogenated jojoba oil appears unsatisfactory as a mold-release agent and as a plug for making molded objects; too many fracture lines develop as the molten wax cools and solidifies. However, a small amount of additive (such as polyethylene or another wax) destroys the crystallinity. Such combinations, though still requiring much research, may prove to be valuable industrial

products in the future. Hydrogenated jojoba wax may also prove valuable as a hardening agent for existing molding-wax formulations. Partially hydrogenated jojoba oil gives soft white waxes whose properties are yet unknown, but they may have important potential in lipstick and cosmetic manufacture.

JOJOBA SEED MEAL

A by-product of jojoba seed is the meal remaining after the oil has been extracted. It should prove of particular interest to livestock producers in arid areas where the plant is grown. The meal contains 26 to 32 percent protein, as well as carbohydrate and fiber. Its amino acid analysis is shown in Table 7. Of the essential amino acids, the lysine content is good, but the methionine content is poor. The nutritional effectiveness of jojoba meal in animal feeds is very uncertain at present because of an unusual toxic factor in the meal. The meal contains an unusual material, simmondsin (Figure 8), whose ingestion causes laboratory rats to avoid food, even their regular

TABLE 7 Amino Acids in 1-Year-Old Nuts After Extraction of the Wax by Pressure, Followed by Solvent Extraction with Hexane

Amino Acid	Grams of Amino Acid per 100 g of Meal	Percentage of Amino Acids
Lysine[a]	1.4	5.7
Histidine	0.6	2.5
Arginine	1.9	7.8
Aspartic acid	2.6	10.6
Threonine[a]	1.3	5.3
Serine	1.3	5.3
Glutamic acid	3.2	13.1
Proline	1.5	6.1
Glycine	2.4	9.8
Alanine	1.1	4.5
Cystine (half)	0.6	2.4
Valine[a]	1.5	6.1
Methionine[a]	0.1	0.4
Isoleucine[a]	0.9	3.7
Leucine[a]	1.8	7.3
Tyrosine	1.1	4.5
Phenylalanine[a]	1.2	4.9
TOTAL	24.5	100.0

Source: D. M. Yermanos, private communication.
[a]Essential amino acid.

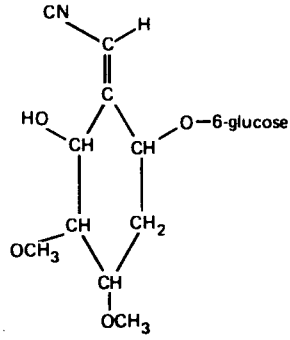

FIGURE 8 Simmondsin.

diet, to the point where they die of starvation. Its effect on ruminants (if any) is unknown at this time. Although the appetites of laboratory rodents are suppressed by simmondsin, ground squirrels, desert chipmunks, mule deer, and rabbits gather and feed on the seeds. Experiments have recently shown that the pocket mouse is able to survive on a jojoba seed diet. Apparently, simmondsin has little or no effect on this animal. (Information supplied by C. Wade Sherbrooke.)

If jojoba meal is to become acceptable as a livestock feed, Food and Drug Administration requirements will have to be met. In this respect, answers are needed to at least three basic questions:

- Does the material cause any adverse effects when fed to livestock (e.g., cattle, swine, and poultry)?
- Are any hazardous compounds transmitted into the meat, milk, or eggs?
- If detoxification is required, is a reliable method available to assay detoxified meal to ensure the absence of toxic factors?

The nutritional value of the protein fed to animals must also be evaluated.

APPENDIX A

Contributors to the Study of Jojoba Utilization

STEVEN C. COHEN, Director of Research, Van Straaten Chemical Company, Chicago

ARCHIE J. DEUTSCHMAN, JR., Professor of Agricultural Biochemistry, The University of Arizona, Tucson

W. R. DUNCAN, Chemist, Magnetic Tape Division, Ampex Corporation, Redwood City, California

CARL A. ELLIGER, Research Chemist, Oilseed Products Research Unit, Western Regional Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Berkeley, California

FREDERICK FAHNOE, Director, Corporate Planning, National Distillers and Chemical Corporation, New York

HARVEY FISHMAN, Director of Research, Bonat, Incorporated

HOWARD SCOTT GENTRY, Desert Botanical Garden, Phoenix, Arizona

F. R. GERBER, Vice President, Gerber Legendary Blades, Portland, Oregon

H. GISSER, Chief, Chemistry Research Division, Pitman-Dunn Laboratory, Frankford Arsenal, U.S. Department of Defense, Philadelphia, Pennsylvania

EDWARD F. HAASE, Jojoba Project Coordinator, Office of Arid Lands Studies, The University of Arizona, Tucson

LE MOYNE HOGAN, Professor of Horticulture, The University of Arizona, Tucson

JACK D. JOHNSON, Director, Office of Arid Lands Studies, The University of Arizona, Tucson

D. A. LEE, Supervisor, New Product Development, The Elco Corporation, Cleveland, Ohio

ROBERT G. McDANIEL, Associate Professor of Agronomy and Plant Genetics, The University of Arizona, Tucson

W. G. McGINNIES, Arid Lands Ecologist, The University of Arizona, Tucson

SUICHI MATSUO, Technical Development Center, Americas, Mitsui & Company, Ltd., New York

WILLIAM P. MILLER, Acting Chief, Division of Industrial and Tourism Development, Bureau of Indian Affairs, U.S. Department of the Interior, Washington, D.C.

THOMAS K. MIWA, Chemist, Northern Regional Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Peoria, Illinois

R. E. MORRIS, Chemical Products Section, Industrial Chemicals Division, The Procter & Gamble Company, Cincinnati, Ohio

LAMBERT NOLINE, Manager, Apache Marketing Cooperative Association, San Carlos, Arizona

J. W. PARKER, Director, Bio-Science Laboratory, Corporate Technical Service, Purex Corporation, Ltd., Carson, California

CARL S. REHNBORG, Executive Vice President, Nutrilite Products, Inc., Lakeview, California

B. L. REID, Professor of Poultry Science, The University of Arizona, Tucson

JOEL SCHECTER, Acting Director, Research and Development Authority, Ben Gurion University of the Negev, Beer-Sheva, Israel

JAMES J. SPADARO, Research Leader, Food Products Research, Engineering and Development Laboratory, Southern Regional Research Center, Agricultural Research Service, U.S. Department of Agriculture, New Orleans, Louisiana

J. A. STEARNS, Senior Project Engineer, Saginaw Steering Gear Division, General Motors Corporation, Saginaw, Michigan

J. WARREN STULL, Professor of Dairy Science, The University of Arizona, Tucson

ANTHONY C. WAISS, JR., Research Leader, Oilseed Products Research Unit, Western Regional Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Albany, California

CHARLES W. WEBER, Associate Professor of Biochemistry and Nutrition, The University of Arizona, Tucson

MICHAEL A. WELLS, Assistant Professor of Biochemistry, The University of Arizona, Tucson

E. B. WESTALL, Vice President, Lakeview Operations, Nutrilite Products, Inc., Lakeview, California

JAIME WISNIAK, Dean, Faculty of Engineering Sciences, Ben Gurion University of the Negev, Beer-Sheva, Israel

APPENDIX B

Selected Readings

A newsletter, *Jojoba Happenings*, is published six times a year by an informal "International Committee for Jojoba Development." Interested individuals can receive this publication without charge by writing to: The Jojoba Coordinator, Office of Arid Lands Studies, The University of Arizona, 1201 East Speedway, Tucson, Arizona 85719.

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