Organic Chemicals from the Chihuahuan Desert

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A consideration of social, economic, political, and technological factors in the search for new renewable sources of raw materials suggests the exploitation and development of the resources of marginal land regions. Desert regions on the North American continent, which cannot be used for food production, nonetheless, grow a variety of indigenous floral species which offer, in their chemical composition, possibilities for agroindustrial development. Prospects for utilization of the resources of the Chihuahuan Desert for the production of organic raw materials are presented. Research and development projects presently underway in Mexico for the commercialization of plants such as Guayule (*Parthenium argentatum*), Creosote Bush (*Larrea tridentata*), Candelilla (*Euphorbia antisyphilitica*), and Palma (*Yucca filifera*), among others, are documented. Raw materials obtained from such plants are characterized, with emphasis on the identification of components of industrial interest. Current bench and pilot plant activities, as well as process and product development requirements, are detailed.

Since 1974 the oil crisis has been reflected in the cost of intensive agriculture and many specialists in this field are becoming worried. In a recent meeting sponsored by the National Science Foundation[1] the future of agriculture was analyzed in terms of the cost impact that oil shortages and price hikes would have. By 1985 energy use distribution for irrigation agriculture in the U.S. is shown in Table I,[2] agricultural machinery fuel and irrigation, together with fertilizers, represent the main areas of consumption and efficiency needs to be improved in these areas so that specific crop costs continue to be competitive. Energy consumption per crop[3] and alternatives to irrigation of dryland farming have also been analyzed. Table II shows energy requirements for major U.S. crops, expressed in thousands of kilocalories, for the production of one unit of product, and the impact of change from irrigation to dryland farming can be seen.

The need for new crops or to improve existing ones is emerging, a search for varieties that, even if their growth is less intensive, will be able to survive in a future insecure fuel supplies. By the year 2000 it is predicted that food and materials agriculture in the U.S. will have new species, acclimatized to produce in drought conditions. In this situation economic returns will have to come from a balance between productivity per hectare and energy input.

Some of the ideas analyzed characterize one of the most important phenomena of modern agriculture—"The Green Revolution"—which emerged from the development of high-yield species of wheat and rice in Mexico and the Philippines.[4] In just 20 years—1950 to 1970—corn production rose from 700 to 1300 kg/ha and that of wheat from 750 to 3200 kg/ha. In the mid-1960's, Mexico stopped importing grains and became an exporter. Between 1964 and 1969, 5.4 million kg of corn, 1.8 million kg of wheat, and 0.34 million kg of beans were exported. The success of this move, however, was temporary;[5] by 1970 the first signs of decreased productivity appeared, and Mexico again has to import grains.

The "Green Revolution" is energy intensive and causes environmental deterioration and conflicts in the economic and social systems. Another more serious consequence is that research and development efforts of developing countries like Mexico have concentrated on a few crops which need high technology inputs and are dependent on external help, so that the search for alternatives using local raw materials has been dangerously delayed.

For many years all investment has been channeled toward high yielding crops for exploitation in selected geographic regions. This has caused unemployment and has diverted attention from regions which have natural resources that can be used with well-structured research and development models, especially in semiarid areas which have become a permanent, passive witness to conventional agriculture. Attempts to integrate these regions into any economic development plan have been limited. There is a need to rescue the deserts and preserve their ecological characteristics. These areas must be considered in the search for plants which are renewable sources of industrial materials and chemical products and would not be produced in potential food-producing regions. The dichotomy of tropical zones and semidesertic regions exists in numerous countries and, to date, no coordinated attempt has been made to use these areas. However, there is still reason to be optimistic and predict that, in the words of G. T. Seaborg,[6] "through new research in plant genetics, soil, science, hydrology, ecology, and any other fields, we must

Table I. Energy Use in Crop Production and Percent Distribution Forecasted for 1985[2]

inputs	10^{12} kcal	percent
fuel for machinery	169.573	57.99
pesticides	7.374	2.52
nitrogen fertilizers	36.455	12.47
nonnitrogen fertilizers	7.207	2.46
crop drying	13.056	4.46
irrigation	41.456	14.18
transportation	17.317	5.92
total	292.438	100.00

Table II. U.S. Average Fossil Fuel (in 1000 kcal) Required to Produce One Unit of Output, by Crop[3]

crops	unit	dryland crops	irrigated crops
corn grain	bu	16.415	30.832
corn silage	ton	116.588	154.162
cotton	bale	1675.731	2963.243
legume hay	ton	364.705	632.963
nonlegume hay	ton	555.992	656.716
sorghum grain	bu	19.096	32.182
sorghum silage	ton	109.746	122.062
soybeans	bu	17.127	59.806
wheat	bu	20.856	37.435

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Figure 1.

learn to support new types of agricultural systems in parts of the world that have resisted previous efforts to such developments".

THE WORLD'S DESERTS

Thirty percent of the continental surface consists of desert regions.[7] There are also huge semiarid areas and savannas. The criteria for classifying a region as desert or semidesert are numerous but nearly all take the annual rainfall into account, with the outside limit being 10 in. Thermal criteria,[8] with subdivision of hot, mild, cool, winter, cold winter, are also used; however, the lack of rainfall is an unquestionable characteristic on arid and semiarid climates. With respect to rainfall there are more than two dozen classification techniques developed with different aims, such as to explain natural vegetation distribution. A recent UNESCO[9] publication mentions 19 different mathematical formulas by which rainfall can be calculated using records of rain and evaporation temperature and relying on the balance of humidity in the upper surface and in the root zone of the vegetation cover.

Theoretically any area of the globe can become a desert if at some point there is a shortage of rainfall. All the vegetation will dry up, the ground will erode, and in a short time the area will become a desert. Rain, solar radiation, CO_2, ground, and climate characteristics have combined to generate desert and semidesert regions which are perfectly identifiable, the distribution of which is by no means a product of chance. Almost all are found in subtropical regions along the tropics, making up two belts which circle the Earth. Some of the most commonly used classifications are subtropical, cool coastal, rain shadow, continental interior, and polar deserts.

The northern hemisphere has the Saharan Desert in Arabia, Syria, Jordan, Iraq, Baluchistan, and West Pakistan, as well as the Sonoran, Chihuahuan, and Mohave Deserts shown in Figure 1. The southern hemisphere has the Kalahari Desert of South Africa, the Australian Desert, and small areas in western Argentina and northern Chile.[10]

Table III. Major Plant Communities of the Earth[12]

	area, 10^6 km^2	plant mass, 10^{15} g of C
tropical rain forest	17.0	344.0
tropical seasonal forest	7.5	117.0
temperate evergreen forest	5.0	79.0
temperate deciduous forest	7.0	95.0
boreal forest	12.0	108.0
woodland and shrubland	8.5	22.0
savanna	15.0	27.0
temperate grassland	9.0	6.3
tundra and alpine meadow	8.0	2.3
desert scrub	18.0	5.9
rick, ice, and sand	24.0	0.2
cultivated land	14.0	6.3
swamp and marsh	2.0	13.5
lake and stream	2.0	0.02
continental total	149.0	826.5

Due to the great expanse of land and distance from the sea combined with the presence of high mountains, continental interior deserts are generated. These are places with high pressure whose cold air center is continually expelled. These deserts are also called "relief" deserts[11] with some of the most characteristic being those of Asia (the Takla Makan and the Gobi), and North America (Chihuahua). Although these deserts are only a small area in comparison to the Earth's surface, geologically speaking they are the most evolved.

In the deserts, solar energy, an essential element for biosynthesis, is so strong that the plants have to protect themselves from it. Carbon dioxide (another requisite for biosynthesis) is also found; however water, a fundamental element, is scarce. Plants that have managed to survive in the deserts have had to adapt, over thousands of years, to be able to live in drought conditions.

In a recent work, R. N. Whittaker et al.[12] showed the production of biomass by geographical regions where, for 149 million continental square kilometers, the scrub deserts were 12% of the total area and accounted for only 0.7% of the vegetation production. Table III gives these data as well as the net production of carbon (10^{15} g/year) which is 1.2%. In general terms, the desert's potential vegetation is insignificant if woods and tropical jungles are also considered.

Vegetation clearly reflects the influence of climate factors. The balance between plant and environment is metastable, and easily destroyed, especially by the intervention of man and climatic changes.

Only a limited number of plant types have adapted themselves to these regions and they can be scattered over large areas. There are two main groups of plants, annuals and perennials, with gramineas being in the first and cacti in the second group.

In the most arid regions of the North American continent, deserts exist where rain falls only once a year; however they still have dense plant populations made up of cacti and other plants (which probably emerged from the Cenozoic age). In some of the North American continental interior deserts the plants evolved by reducing their foliage area to avoid evaporation, displacing chlorophyll to the trunks, and changing the cellular structure of the trunk in order to store large amounts of water during long periods of drought. Cacti and many other plants evolved using this and similar mechanisms.

Gradually, regions like the Chihuahuan Desert began to appear with very diversified flora, where cacti can be found together with numerous species of agaves and yuccas. The discussion in following paragraphs will focus on the potential of this flora as a source of raw materials for industrial purposes.

THE CHIHUAHUAN DESERT

Chihuahuan Desert is an interior continental arid desert which covers 500 000 square kilometers in southern Texas, New Mexico, and part of the States of Chihuahua, Coahuila, Durango, Zacatecas, Nuevo León, and San Luis Potosí in Mexico. Apparently it is the only desert in North America that is isolated from the others—Sonora, Mohave, and Grand Basin; however it is thought that it once belonged to a much larger desert complex. Altitude varies between 900 and 2000 m, with summer rather than winter rainfall and generally lower temperature than the Sonoran and Mohave Deserts. Climatological and geographical factors make differences in flora here very marked compared to other deserts; cacti are smaller and there are many species of yuccas and agaves. The Chihuahuan Desert is perhaps one of the best examples of massive use of plants as sources of raw materials with industrial potential; however, this experience has been gained only by using wild stands.

The mountain chains in this desert run from north to south, causing an interesting diversity of flora in each of the numerous geographical microregions. Experience in the handling, use, and even improvement (as in the case of guayule) of some of the Chihuahuan Desert plants is abundant. Some industrial materials which have been produced and continue to be extracted from Chihuahuan Desert plants are Candelilla wax (*Euphorbia antisyphilitica*), Ixtle (the generic name for hard fibers obtained from *Agave lecheguilla*, and *Yucca carnerosana*), and they continue to be one of the principal employment sources in the region. Also, from 1902 to 1950 rubber was produced from Guayule at 19 industrial plants distributed around the Chihuahuan Desert.[13] All the above-mentioned materials are produced and exported from the ecosystem; however, numerous shrubs are used locally for fuel, e.g., mezquite (*Prosopis juliflora*), and food is collected from such plants as the prickly pear (*Opuntia streptacantha*) and nopal (*Opuntia spp*). Possibilities for exploitation are still greater. Existing phytochemical information needs to be analyzed to generate alternatives; however, this analysis must be part of a general plan which takes present demands into account and forecasts future needs of chemical products and materials.

The growing concern with future material and chemical product supply problems[14] has generated new strategies and models for handling renewable resource use alternatives. Most of these models have been based on forestry products, but models are now being developed for marginal areas, such as the deserts.[15]

The combination of resource management, agronomy, engineering, forecasting, etc., handled efficiently and with clear perspectives of the ecosystem's internal social needs and the demands for low-cost products for the outside market, are the ingredients for meeting the challenge which development of these regions implies (which in Mexico alone covers 50% of the total territory and approximately 15% of the population).

The Chihuahuan Desert flora contains at least 100 families with 591 genera and about 2000 species. The most important families are listed in Table IV where species with the greatest industrialization possibilities and use as food and fodder are mentioned. Some genera, such as *Larrea* (Zygophyllaceae), only have one species, *Larrea tridentata*. However this is widely distributed in all North American deserts (with different grades of chromosome endowment)[16] and is one of the most abundant species.

Table IV. Principal Plant Families of the Chihuahuan Desert

family	no. of genera	no. of species
Amaryllidaceae (most important genera: *Agave*. Hard fiber is obtained form *Agave lecheguilla*)	3	28
Liliaceae (most important genera: *Yucca*. Fiber is obtained form *Yucca carnerosana* and steroids from Yucca filifera)	14	45
Cactaceae (most important genera: *Opuntia*. Food consumption, contain alkaloids, sugars, gums, pigments, etc.)	35	214
Euphorbiaceae (most important genera: *Euphorbia*. Candelilla wax is obtained form *Euphorbia antisyphilitica*).	10	52
Leguminosae (most important genera: *Prosopis* and *Acacia*. Contain alkaloids, proteins, and essential oils amongst other things)	33	116
Cruciferae (most important genera: *Lesquerella*. Contains a high percentage of oil in the seeds)	10	18
Solanaceae (most important genera: *Datura*. Contains alkaloids)	9	29
Compositae (most important genera: *Parthenium*. Rubber is obtained form *Parthenium argentatum*)	83	227
Gramineae (Pasture species used to feed cattle, both green and dry)	99	407
Zygophyllaceae (most important genera: *Larrea*. A resin containing NDGA, flavonoids, and lignanes is obtained from *Larrea tridentata*)	6	6
	302	1142

In the following pages a scheme is developed and the alternatives that the Chihuahuan Desert offers are presented, together with Mexico's experience since 1974.

MATERIALS FLOW: TOWARD SYSTEMATIZATION

The 20th century has seen a specialization in forestry science and several models have been developed to handle the different material flows. However, as a consequence of this modern age of permanent substitution, it is necessary to widen perspectives especially in the use of byproducts.

Analysis of material flows in low biomass producing desert zones has not been possible in any depth. The possibility of intensifying this flow and simultaneously promoting increased vegetation cover needs to be studied. In the few examples (many in the Chihuahuan Desert) of use of desert biota for obtaining industrial materials, the same handling systems for the resource and productivity levels have been maintained for decades, decreasing technical competitiveness and costs. In these regions, in spite of the general phenomena of unemployment, various activities compete for the labor force: mining, livestock, agriculture. For this reason it is important to develop a model which will promote a regional level analysis of material flows (renewable and nonrenewable) and their

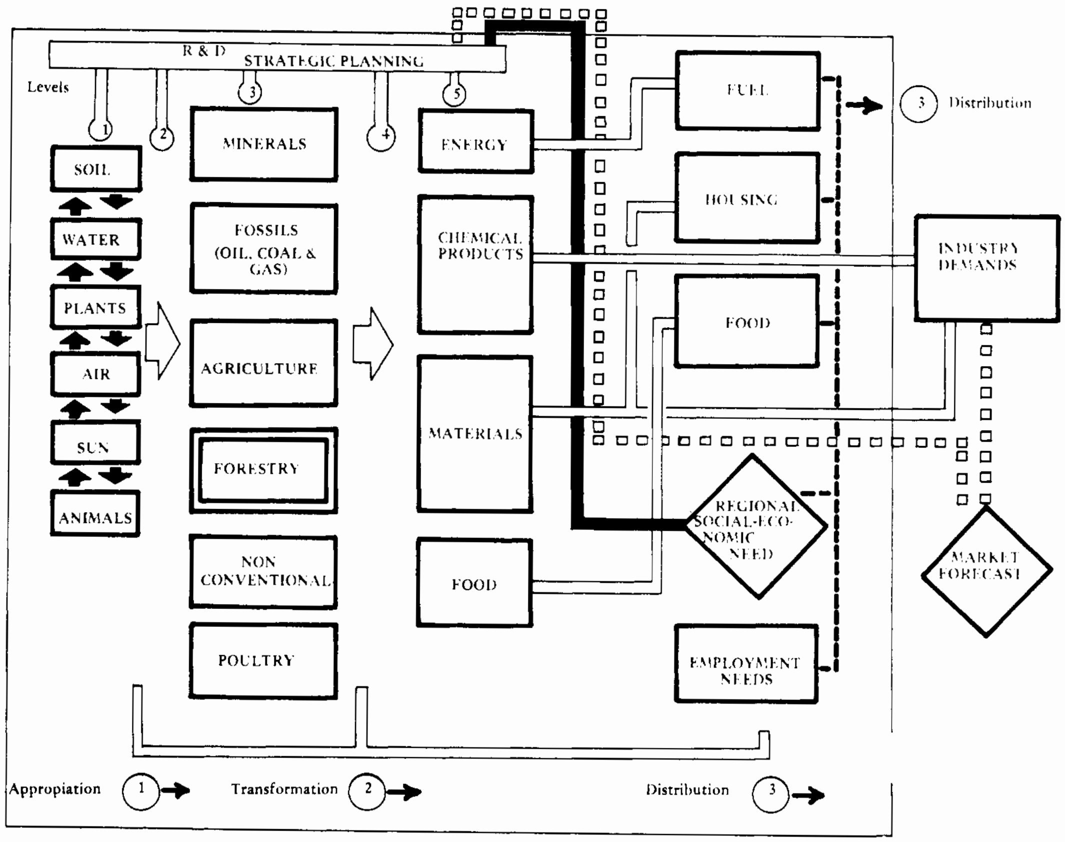

Figure 2. Material flow diagram and R&D levels.

economic and social impact at regional and national levels.

Uses for various desert plants are frequently proposed; however only qualitative phytochemical information is taken into account. With this information applications are invariably proposed without knowing the necessities of the chemical on material industries.

In developing countries one of the main problems of technology transfer has not been able to incorporate local raw materials into the imported technological processes. Important areas of industry, where the possibility of substituting local raw materials (plastics, paints, rubbers, textiles, pharmaceuticals, etc.) exists, seem to be too dynamic for the weak regional research and development structure.

Since 1974 the Mexican National Council for Science and Technology (CONACYT), the Mexican National Commission for Arid Lands Studies (CONAZA), and the Applied Chemistry Research Center (CIQA) have been investigating renewable resources from the Chihuahuan Desert. The knowledge accumulated during this time and the need for a systematic regional analysis has gradually led to the definition of a broader scheme for materials flow, although in a preliminary stage it is worth mentioning some of its elements.

Figure 2 shows the different components that intervene in material flows. Using this scheme an R&D program can be proposed for the renewable resources of the Chihuahuan Desert. Contrary to previous proposals, it is hoped that the process of strategic planning will be initiated with the establishment of two types of information. (1) *External Market Demand*: Made up of the national or international forecasted demands for plastics, rubbers, pharmaceutical products, etc. (2) *Regional Social Needs*: Local requirements of food, housing, fuel, and employment and the social assessment of the new technologies.

Besides considering present needs, within these two large areas, forecasting must be done in selected fields. Organic raw material requirements can be split into the four large groups shown in Table V.

Table V. Raw Materials Classification

- Fuel
  - Especially for local consumption, obtainable directly or from agricultural wastes
- Chemical Products
  - The demand for this type of product will come from the national industry (or international in some cases). Due to its complexity this group has been divided into the following areas:
    - products with biological activity (veterinary, pharmaceutical, phytoactive, and pesticide use)
    - soaps and detergents
    - cosmetics
    - organic coatings (adhesives and varnishes)
    - plastics additives
    - rubber additives
    - dyes
    - lubricants
    - others
- Materials
  - This area includes local needs, especially in housing, as well as external demand for fibers and certain types of polymers and waxes
    - pulp and cellulose
    - textiles and fibers
    - wood
    - resins and waxes
    - rubber and other noncellulosic polymers
- Foods and Fodder
  - Only for local consumption
    - sources of proteins
    - carbohydrates
    - fats and oils
    - others

Simultaneously Data Base must be established, by plant species and containing information on the chemical composition, botanical and ecological indicators, abundance, location, etc. Often the chemical composition of selected species must be verified so that the transformation alternative process and other R&D needs can be planned on the five levels shown at Figure 2.

Research and Development. *First Level. Ecology.* Interrelationship between the biotic and abiotic elements: water, soil, plant, animals and solar energy.

Second Level. Appropriation. A stage which consists of the resources appropriation: cultivation, reforestation, or use of the wild species alternatives, selection of varieties, harvesting method, transportation, storage, labor, etc.

Third Level. Chemistry and Biochemistry. A third level in which there is a return to the basic studies of the chemical composition and biochemistry of the different varieties of plants and the generation of extractive methods on a bench scale.

Fourth Level. Transformation. The transformation process which means the need for research at pilot level, use of byproducts, and basic engineering studies.

Fifth Level. Products Development. Finally, the development of the product, determining competitiveness and substitution capacity, semicommercialization, joint work with industry, and finally integration of the technology to be transferred to the company or federal organization responsible for its implementation.

The level order represents only its position in the hypothetical (sometimes real) production flow—appropriation, transformation, and distribution. Each level is integrated by numerous activities that are strategically located along the R&D project according to the priorities in terms of the information required at the several evaluation stages.

Using some of these criteria, in the following section the possibility of certain Chihuahuan Desert plants satisfying future demands are analyzed.

RAW MATERIALS FROM CHIHUAHUAN DESERT FLORA

As already mentioned there are at least 2000 plant species in the Chihuahuan Desert, many of them characteristic of this region. Phytochemical information is plentiful although extremely specialized and scattered and in many cases the information about a resource is on the chemical structures a family of chemical compounds and generally is qualitative. Quantitative information on the presence of a specific substance for the goals that one wants to reach is invariably needed.

In this section the chemical information available on Chihuahuan Desert flora, with special emphasis on the ten families mentioned, is presented in the four large groups of raw materials. Logically, because of the great amount of information available, only the species considered important in each family are mentioned.

Fuels. The use of renewable resources as an energy source is one of the most important fields of the future[17] in that traditional energy sources have to be gradually substituted. Man will partially return to the woods in his search for the fuel necessary to satisfy his needs.

Generally the use of this energy source is local and is very important in developing countries;[18] the consumption of wood and organic wastes as sources of fuel in Northern Mexico represents about 25%. Presently the Chihuahuan Desert has the following alternatives.

Plants. The total use of the plant, especially mesquite, can be an excellent local energy source using reforestation and adequate management.

Agricultural Waste. About 100 000 tons of cellulose residue (dry base) are generated annually from the use of Candelilla which, although presently used inefficiently, in the future when better extraction methods are available for this product, a fuel unit could be established feeding with this waste. Another important residue is that left after the extraction of the fibers from ixtle (Lechuguilla and Palm). A serious problem is encountered with the extraction of these products as this is done at the place of collection and the residues are left on the ground (although they are sometimes used locally as fuel). In the future, when Guayule production takes place on an industrial level, a plant which produces 5000 tons of rubber annually will generate between 40 000 and 50 000 tons of waste, which will feed the industrial plant's consumption.

Table VI. Species from the Chihuahuan Desert with Possible Pesticide Action

species	comments	action
Ricinus communis	substances in the leaves	insecticide[21]
Larrea tridentata	substances in the leaves	fungicide[22]
Anagallis arvensis	substances in the plant	fungicide[23]
Datura stramonium	alkaloid in the plant	nematodicide[24]
Nicotiana glauca	alkaloid in the plant	aphidicide[25]

Chemical Products. Industry is one of the most complex sectors for a program of this nature. On the one hand there is the diversity of substances employed in the modern chemical industry; then there are the rigorous technical processes needed to produce a high quality of raw materials;[19] and finally the monopolic structures in which a subsidiary of the company generally manufactures the additives required. The dynamism of the chemical industry and especially some sectors such as plastics, pharmaceutical products, and pesticides means that the life span of some products is only a few years, which is why a substitution program must consider and forecast the raw materials scene in 5–10 years.

As in many other countries, the chemical industry in Mexico is the most dynamic sector and has developed a growth rate of 13.4% annually, tripling its production index in the decade between 1965 and 1974.[20]

Biologically Active Products. Table VI shows some of the main plants reported in the literature as containing biologically active substances that have possible pesticide applications.

Antibiotics. Extracts from *Aloe vera*[26] have an antibiotic action, an effect also found in the cactus *Lophophora williamsii*.[27] The main component is called peyocatin and has an antibiotic effect against a wide range of bacteria and fungi.

Pharmacological Products. There is a general idea that prescription drugs are mainly of synthetic origin; however, in the United States during 1973, 25% contained one or more ingredients extracted from plants, with a total value of about 3 billion dollars. In the USSR roughly 40 000 tons of medicinal plants are needed, both from wild and cultivated sources.[28]

The following compounds are among the most important obtained from plants and used as drugs in the U.S.: steroids (95% diosgenin), codeine, atrophin, reserpin, ephedrin, scopolamin, digitoxin, and many others. A recent study[29] stresses the important role that plants continue to play as sources of active compounds in modern pharmacopoeia.

Among the plants from the Chihuahuan Desert the existence of sources of alkaloids, steroids, and hypoglycemiants is well known. Table VII shows the most important of these. As can be seen, Agave and Yucca are potential alternatives for the obtention of raw materials (steroids)

Table VII. Chihuahuan Desert Plants Containing Substances with Pharmacological Activity

species	compound	concn
	Steroids[30]	
Agave crassispina	manogenin	0.9 g × kg (dry)
Agave ferox	manogenin	1.7 g × kg (dry)
Agave lechmanii	manogenin	0.8 g × kg (dry)
Agave paressana	manogenin	0.8 g × kg (dry)
Agave quiolefera	manogenin	0.3 g × kg (dry)
Agave salmiana	manogenin	1.1 g × kg (dry)
Yucca endichiana	sarsasapogenin	1.1 g × kg (dry)
Yucca filifera	sarsasapogenin	100.0 g × kg (dry) (seed)
Yucca jalicensis	sarsasapogenin	0.4 g × kg (dry)
Agave funkiana	smilagenin	0.8 g × kg (dry)
Yucca elephantipes	smilagenin	0.6 g × kg (dry)
Agave stricta glauca	gitogenin	1.5 g × kg (dry)
Agave stricta nana	gitogenin	1.1 g × kg (dry)
Maguey canon del abra	tipogenin	0.4 g × kg (dry)
Agave melliflua	sitosterol	0.1 g × kg (dry)
Maguey mescal azul	sitosterol	0.2 g × kg (dry)
Maguey mescal nana larga	sitosterol	0.4 g × kg (dry)
	Alkaloids	
Lophophora williamsii[31]	mescalin	
Ariocarpus retusus	hordenin	
Ariocarpus retusus	*N*-methyltyramine	
Datura stramonium[32]		
Datura meteloides		
Ephedra sp.[33]	ephedrin	
Nicotina glauca		
Acacia angustissima[34]	*N*-methyl-β-phenylethylamine	0.028%
Acacia constricta	*N*-methyl-β-phenylethylamine	0.020%
Acacia gregii	*N*-methyl-β-phenylethylamine and tyramine	0.016%
Acacia texensis	*N*-methyl-β-phenylethylamine and tyramine	0.008%
Prosopis glandulosa	*N*-methyl and tyramine	0.310%
	Hypoglycemiants	
Agave lecheguilla[35]	xylitol	
Opuntia ficusindica[36]	saponine	

from the desert. In some cases technical problems make obtention difficult, especially in some Agave and those which simultaneously have similar compounds. However, in others, such as the Yucca, the sarsasaponin is found alone.[37] In particular, *Yucca filifera*[38] shows great potential and a research and development project in more detail later.

Soaps and Detergents. Traditionally in the Chihuahuan Desert various plants have been used as sources of detergents for washing clothes and shampoos. With the advent of modern surface-active agents, many of these plants disappeared from the urban regional market; however, they are still used on a local community level and because of the problem caused by lack of biodegradability of the synthetics, some of the plants of this region may even have possibilities on a commercial level (in the U.S. some shampoos have recently appeared which use extracts of Yucca). Among the species best known for this end use are (1) different species of the genera *Solanum*, which contains solanin in varying quantities; (2) numerous *Agaves* such as *A. schotti* and *A. lecheguilla*; and (3) *Cucurbita foetidissima*. In all these plants the saponine play an important role as a detergent.

Cosmetics. The mucilage from Opuntia is found among the Chihuahuan desert flora. In the perfume area, some *Acacia*, especially *A. farnesiana*, show possibilities in the production of essential oils; however, to date no feasibility studies have been done. Some waxes, like that of Candelilla, already have cosmetic applications in the manufacture of lipsticks.

Organic Coatings. In this area Mexican production of plywoods during the last 10 years climbed from 69 000 to 118 000 tons in 1975.[39] Some of the products obtained from Chihuahuan Desert plants can be used in this field, as recent experience has shown. The resins obtained from the leaves of *Larrea tridentata*[40] and Guayule[41] and the phenolic extracts from mesquite (*Prosopis juliflora*) show possibilities in this field of application. In the area of paints and varnishes there are different resins, drying oils, and semidrying oils that can be used. The oils from *Ricinus communis*,[42] *Yucca filifera*,[43] *Cucurbita foetidissima*, and Guayule resin[44] also have possibilities. The mucilage from Opuntia could also have an important application in adhesives, especially considering the abundance of this genera.

Plastic Additives. The thermoplastic and elastomer industries are an innovative area, especially because of the need to improve mechanical and other properties. Therefore the need for additive products, apart from being large in volume, is very diverse: plasticizers, stabilizers, pigments, antioxidants, ultraviolet filters, etc., are some of the additives used daily in the transformation of thermoplastics into a finished article. Special attention should be paid to the development in PVC consumption, especially because PVC needs the most additives. In Mexico PVC production doubled between 1968 and 1975, reaching 49 000 tons.[45] In this same year the U.S. produced 1 643 000 tons.[46] The volume of additives required for future expansion must include the growth in use of additives obtained from renewable sources, such as epoxydized oils. The epoxydized derivatives of *Yucca filifera* seed oil lower the glass transition temperature (T_g) of PVC in the same way as commercial plasticizers of the same type.[47] The effect on induction time in the dehydrohalogenation and on migration in the same thermoplastic show similar behavior. The oil of *Ricinus communis* is already used commercially; however, on a regional level no thought has been given to the possibility of cultivating this plant.

Elastomer Additives. Since the oil embargo, when the shortages of fossil fuels became apparent, natural rubber has recouperated in price, which was at its lowest level[48] until 1972. Hopefully the recovery will continue. The role of rubber in the world market is assured and in spite of the fact that antipollution laws in some countries will induce a decrease in the manufacture of vehicles, in others, especially developing countries, manufacturing will increase to be gradually incorporated by a larger sector of the population as they reach a level of economic accessibility. The consumption of natural and synthetic rubbers will also be positively affected by the increased use of agricultural machinery.

Manufacture of any rubber article, including tires, requires numerous additives which are needed in large quantities, especially carbon black, and in lesser amounts but with higher prices, oil, extenders, antioxidants, peptizers, antiozonants, fillers, etc.

Some products that can be obtained from Chihuahuan Desert resources are as follows: (1) Antioxidants, obtained from *Larrea tridentata*. (2) Peptizers obtained from Guayule resin. Recent studies show that milling time of synthetic and natural rubbers is considerably reduced with the use of this material.[49] (3) Waxes, such as that of candelilla, in certain articles.

Presently some of these possibilities are being studied in Mexico.

Dyes. The fruit and flowers of Opuntia have very attractive colors. This is due mainly to the presence of xanthines and cianines and, in some cases, to flavonoids and carotenes. Extracts of these compounds can be used as edible dyestuffs.

Lubricants. The only report that exists about possibilities of a lubricating agent is on *Ricinus communis*, a plant which is already widely cultivated and used in other latitudes.

Others. Some species like *Acacia angustissima*, *A. tortuosa*, and *A. farnesiana* have tannins in their bark which are used in leather tanning. In the latter species these compounds have also been found in the fruit. In the heart of mesquite wood (*Prosopis juliflora*), concentrations of tannins have been found to vary between 5 and 9%,[50] with 5% concentration in the bark. Besides being used as tanning agents their range of application has widened to include usage as mud drilling dispersors, and by alkaline sodium fragmentation phenolic organic substances with low molecular weights can be obtained.[51]

Materials. As already mentioned, preindustrial man depended about 80% on renewable resources (animal and vegetable) for his material needs. By the 1970's as a consequence of technological development, this situation has changed drastically. The structure of material consumption in the U.S. showed that man depended 93.4% on nonrenewable sources of materials. In only 200 years the material structure of man, at least in developed countries, has been completely transformed as it can be observed in Table VIII.

The same tendency, although reduced, is seen in developing countries such as Mexico, where during 1970 6.7 kg per capita of polymers were consumed (elastomers, thermoplastics, and fibers) and by 1976 this consumption rose to 15.77 kg. Projections show that by 1982 this quantity will reach 28 kg, although food consumption will not show signs of improvement, as can be seen in Table IX.

Table VIII. Sources of Materials Used in the U.S.[52]

source	%				
sand and gravel	21.2				
stone	20.0				
petroleum	18.3				
coal	11.8				
gas	11.8				
nonmetalic	7.2				
renewable	6.6	forest	96.00%	cotton	0.8%
				fibers	0.9%
		others	4.0%	oils	1.0%
				animal fat	0.9%
				rubber	0.4%
metallic	3.1				
total	100.0				

Table IX. Consumption of Different Foods Compared with That of Polymers in Mexico during 1970–1982

product (consumption in kg/Head)	1970	1976	1982[a]
polymers	6.7	15.77	28.9
rice	5.7	6.3	6.6
beans	16.3	14.0	7.3
potatoes	6.5	7.0	7.3
beef	16.2	18.7	20.1
pork	5.5	6.6	7.5
eggs	12.1	13.8	15.4

[a] Projections done at CIQA. Source: Bank of Mexico and National Association of the Chemical Industry.

One of the major social impacts that synthetic materials have had in Mexico is the displacement of natural fibers (henequen, ixtle) which are all produced from resources obtained in semiarid zones, especially in Yucatan and the Chihuahuan Desert. Another consequence of displacement was observed in Guayule rubber production. The exportation of natural Guayule rubber from its initial use up to the advent of synthetic rubber is shown in Figure 3. Apart from the previously mentioned products there are other examples of products from the Chihuahuan Desert such as Candelilla where the displacement by synthetic waxes, even if not so serious as the case of Guayule, has caused great fluctuations in exportation demand.

Within the ecosystem, materials continue to be used for construction, manufacture of furniture, etc. However, in the Chihuahuan Desert there has not been any systematization or concerted efforts made to increase the flow of materials, internally or externally.

Pulp and Cellulose. The desert's potential to produce pulp and cellulose is mainly concentrated in the residues of plants used for other purposes, although species as *Prosopis juliflora* and Yucca could also be used. Some of the possible alternatives are as follows.

Yucca. Studies have been done on the production of paper from the trunks of various species, especially *Y. elata*, *Y. filifera*, and *Y. decipiens*. However, the use of these species would cause irreparable ecological damage because of their slow growth rate.

Prosopis. It is possible to obtain pulp for paper making from the branches of some species of this genera. In the Chihuahuan Desert there are only two species, but they are quite plentiful.

Opuntia. The whole plant can be used to obtain cellulose with yields of 35–41%. The content of α-cellulose varies between 76 and 81%.[53]

Residues. Cellulose can be obtained from the residues generated by the extraction of other materials such as *A. lechuguilla*, *E. antisyphilitica*, and *P. argentatum*. In the case of Candelilla (*E. antisyphilitica*) plans exist to es-

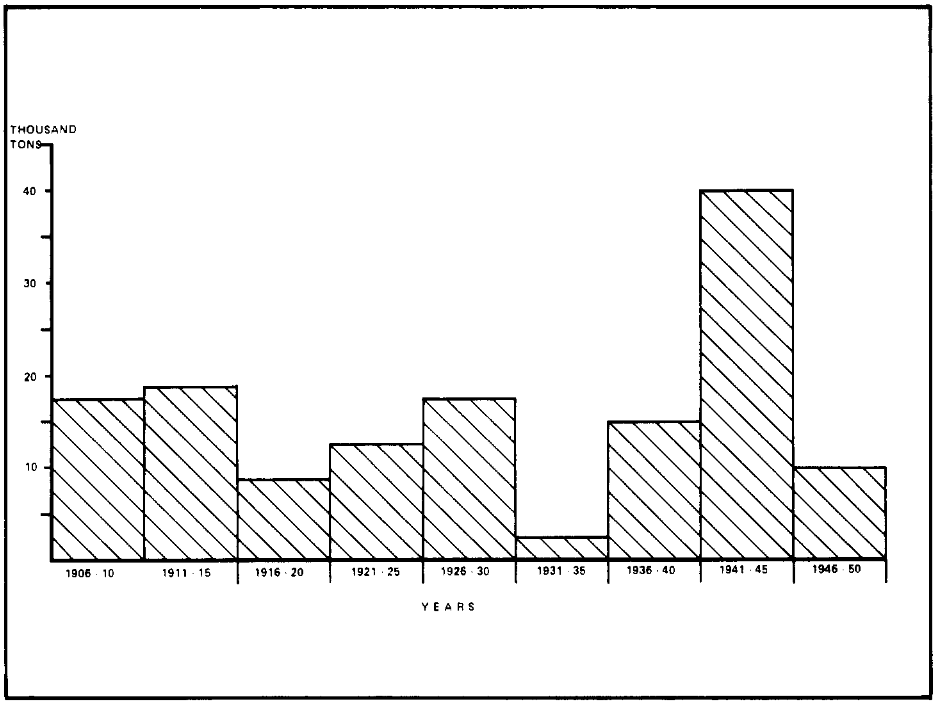

Figure 3. Exportation of guayule rubber from 1906 to 1950.[13]

Table X. Production of Natural Fibers (Noncotton) (Thousands of Tons)[55]

years	jute	others
1966	724	320
1967	686	290
1968	692	306
1969	681	314
1970	641	295
1971	546	283
1972	503	301
1973	479	307
1974	436	302
1975	370	219

tablish a paper factory using the bagasse.[54]

Future studies must be done to show the technoeconomic feasibility and socioeconomic impact on the different options presented.

Textiles and Fibers. Natural fibers, excluding cotton, are fast being displaced and some of the producer countries, like Mexico, have had to return to internal markets of rugs and carpets, etc. The United Nations have noted the decline in jute production which was 724 000 tons during 1966 and decreased to 370 000 tons in 1975.[55]

In the international market of other fibers (sisal, henequen, ixtle, etc.) the situation is less drastic, but even so signs of displacement can be seen. The same U.N. report indicated that in 1966 320 000 tons of natural fibers were produced while only 219 000 were produced in 1975, although 1 year before the production reached 302 000 tons. In Table X production statistics for the decade between 1966 and 1975 are shown.

In the Chihuahuan Desert one of the traditional social activities has been the use of *A. lechuguilla* and *Y. carnerosana* in the production of hard fibers. The quality of these products upon aging compared to synthetic successors is inferior. In Table XI some of the mechanical properties of these fibers are shown compared to Nylon 6 and fiber glass.[56]

Market instability and lack of technological innovation with fibers produced in the Chihuahuan Desert has caused great fluctuations in production. Figure 4 shows production of Chihuahuan Desert hard fibers for the last 10 years.[57]

Table XI. Mechanical Characteristics of Fiber Glass, Nylon, and *Lechuguilla* Fibers[56]

property	fiber glass dry	fiber glass wet	nylon 6	*lechuguilla* dry	*lechuguilla* wet
tenacity, g/den	2.5	1.9	5	2.5	1.7
young modulus, g/den	36.4	17		32.6	23
% elongation (at rupture)	7.2	7.3	24-40	11.4	15.6

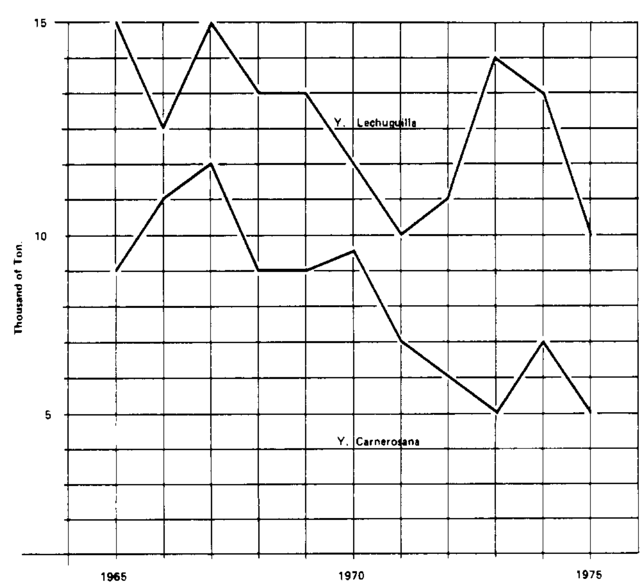

Figure 4. Mexican production of hard fibers.[57]

One of the most important aspects that should be considered in the future is the improvement of the fiber properties, especially resistance to biodegradation. Superficial treatment to reduce high porosity is another aspect that should also be studied.

In the thermosets area experience with Chihuahuan Desert products is reduced to the preparation of bakelite-type materials, in which the phenol is substituted partially or totally with phenolic resins extracted from *Larrea tridentata*.[40]

Rubbers and Other Polymers. The best prospect for the production of hydrocarbons in the Chihuahuan Desert is guayule and Mexico is presently developing a research and development project for the establishment of a production plant with a 5000 ton/year capacity in the preseeable future. This will allow commercial-scale evaluation of the industrialization of this shrub. Similar programs have been adopted in the U.S., where several tire manufacturers have initiated agronomic experiments. The quality of rubber obtained from guayule shows that it has the same application possibilities as *Hevea brasiliensis*. Apart from guayule some Euphorbia contain also polyisoprenic rubber; however its importance compared to guayule is negligible.

Food. The Chihuahuan Desert can supply some foods for its population, although little of it is for direct consumption. Some species contain substances that can be extracted, either for use in daily nutrition, as in the case of oil, or to enrich other food. Although this work's objective is to present a panorama of the qualitative and quantitative capacity of the desert to produce organic compounds, it is opportune to present some of the plants that can also contribute as a direct or indirect source of food or fodder.

Human Consumption. Food is obtained directly from *Opuntia*, *Yucca*, and *Acacia* fruits. There are indirect sources of (1) proteins, mainly from legumes; (2) oils, from the Crucifera family and especially the *Lesquerella* genera, as well as *Cucurbita foetidissima*; (3) carbohydrates, especially mesquite and the Yucca genera with its dates and *Opuntia*.

Animal Consumption. Contrary to popular belief, the Chihuahuan Desert has plentiful food for livestock. (1) Green Plants: Abundant pasture is available in spring and summer with about 386 species of Gramineae. Mesquite (*Prosopis juliflora*) is also a good food source for livestock. In drought periods different species of the *Opuntia* and *Echinocactus* genera can be used both as a source of food and drink. (2) Dry Plants: Various species of Gramineae can be baled for storage. (3) Residues: The leaves of various shrubs, especially guayule and *Larrea tridentata* (although the latter has to be thoroughly deresinated).

New technologies that will promote the use of protein sources must be incorporated in this area. For this reason the evaluation of fermentation systems for biomass production are foreseen for the immediate future.[58]

HIGHLIGHTS OF THE CHIHUAHUAN DESERT RENEWABLE RESOURCES RESEARCH AND DEVELOPMENT PROGRAM

Until 1973 Mexican experience in research and development programs for arid zone renewable resources was limited to few forestry studies, experiments on paper production and phytochemical research. In 1972 the Comisiôn Nacional de Zonas Aridas–Consejo Nacional de Ciencia y Tecnologîa (CONAZA–CONACYT) Program was established with various projects on plants from the Sonoran and Chihuahuan Deserts. In 1974 CIQA, in collaboration with CONAZA–CONACYT, started joint projects which incorporate all states of research and development, such as physical chemistry, materials, pilot plant experimentation, development of products, semicommercialization, feasibility studies, etc. The present state of research on these projects is presented below.

Guayule (*Parthenium argentatum*). This project was started in 1974 between CONAZA–CONACYT and CIQA although from 1972 preliminary studies were being undertaken at the Universidad Nacional Autônoma de Mêxico (UNAM). Mexican shrub reserves (plants of a usable age) were calculated to be three million tons.[59]

Rubber Structure. The microstructure of guayule rubber has been analyzed by different spectroscopic methods (NMR, ^{13}C, ^{1}H, 300 MHz) and found to be identical with that of *Hevea brasiliensis*, at least in the cis 1,4 content.[60] Molecular weights and distribution as well as the dependence of these on weight, geographical location, and other conditions have been analyzed and a greater homogeneity has been found in guayule rubber than in *Hevea*.[61,62] This is apparently due to a higher linearity in guayule which gives it certain advantages, especially for handling in solution, as it has a very low gel content. Studies on the ramification level and relationship with the material's crystallinity are in progress.

Rubber Technology. Guayule rubber produced in the Mexican Pilot Plant is being evaluated for different uses by both tire and nontire companies on an international level. It has been found that guayule rubber could be an adequate substitute for *Hevea* rubber.[63] One difference that has been found is the low curing rate during vulcanization, which requires a change in formulation. The green strength of guayule is less than Hevea but this is being overcome by use of chemicals.[64] The guayule rubber evaluation program carried out over the last 2 years comprises also different aspects of processability such as milling, mixing, extrusion, and injection.

Pilot Plant. Experimentation at pilot level started in Mexico in 1976, and to date results have been positive both for the product as well as technical and economic feasibility of the process.

Other research and development groups, such as Firestone, have recently started pilot studies of the process. Figure 5 shows the process flow diagram presently being used at the CONAZA–CONACYT–CIQA Pilot Plant.

Agronomy. Past experience in the domestication of this shrub is plentiful.[65] To date different programs have been started: in Mexico the objective is recouperation of rubber from the wild shrub; in the United States experimental fields have been set up, mainly in Arizona, Texas, and California, in which both the Universities and the tire companies, like Firestone and Goodyear, are trying to determine the economic feasibility of guayule as a crop.

Byproducts. Interest in byproducts, especially the resin, is recent. Possible preliminary uses are in varnishes and as peptizer agents in rubbers. The bagasse can be used as fuel for the Plant, and bench scale work is being done on a bagasse fermentation process to obtain biomass fodder.

Government Involvement. From the start, the Mexican project has been developed by the Federal Government (CONAZA, CONACYT, and CIQA) and it is hoped that the establishment of the first productive unit of 5000 tons/year will begin in 1980.[66] In the United States, the Senate recently approved a bill to support research on this resource.[67]

Socioeconomical and Technological Assessment. In Mexico socioeconomical studies of the regions in which Guayule is being developed[68] have been carried out since 1974. Technological Assessment studies began in U.S. in 1978 sponsored by the National Science Foundation and carried out by the University of Arizona and the Midwestern Research Institute.[69]

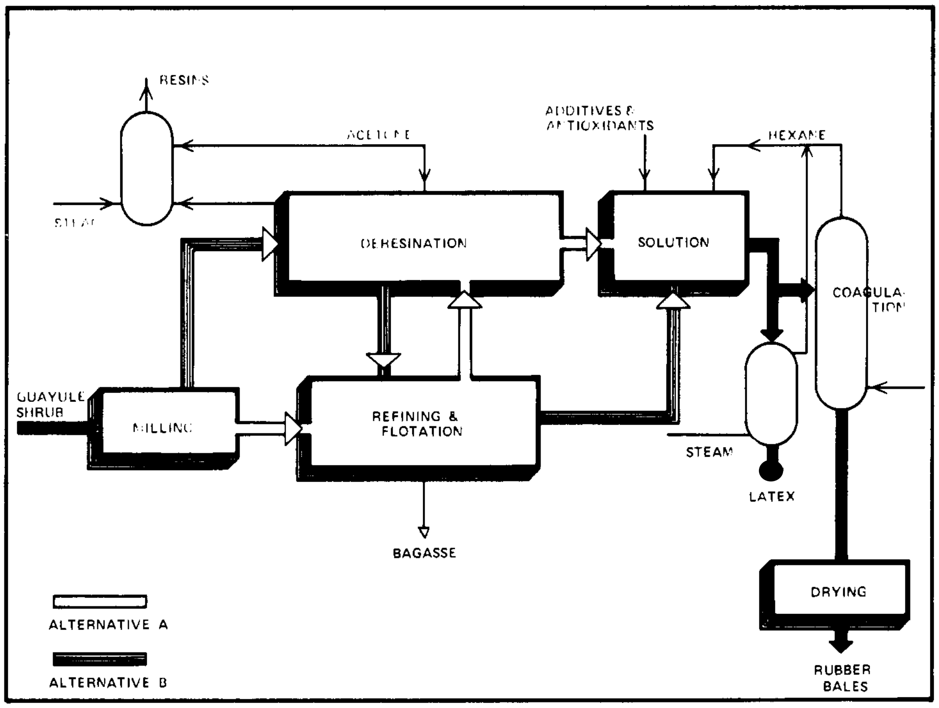

Figure 5. Guayule rubber extraction process experimented at the pilot plant level in Mexico.

International Cooperation. Direct contact has been established between CIQA and the various rubber companies which has promoted the rapid development of end use evaluation. CIQA has also a joint project with the University of Akron's Institute of Polymer Sciences since 1976, on rubber structure and technology, supported by CONACYT and NSF.[70] In 1979 Mexico and U.S. governments signed a general international agreement on science and technology in which guayule project is included in the area of new crops for arid lands.

Perspectives. It is possible that in 10 years guayule will be an important arid zones crop in the southern U.S.; Mexico's approach will take initially advantage of the ecological adaptation of the shrub to the Chihuahuan Desert and will look for intensive reforestation systems.

Creosote Bush (*Larrea tridentata*). Abundant studies done on this plant are on its ecology and chemistry.[71] Because of its abundance, resistance to drought and interaction with elements of the ecosystem, it is one of the most important constituents of the American deserts. In 1974 studies on possible industrial uses began at CIQA, concentrating on the phenolic type resins that are present in the leaves (see following diagram with chemical structures).[72] To date the following results have been obtained.

Antioxidants. Without separating the compounds, fractions obtained from this plant have shown excellent antioxidant activity in different rubbers (natural and synthetic), comparable to commercial products. The studies include evaluation of physical properties during aging,[73] etc.

Fungicides. Fungicidal activity was found against different fungi characteristic to various crops[74] at laboratory level.

Fodder. Studies have been carried out in various U.S. and Mexican institutions to evaluate the use of the deresinated leaf as livestock fodder. The limiting factor is cost;[75] however, it is possible that in the future difficulties with the use of the resin will be overcome and the leaves will be a byproduct.

Wood. Applying the concepts of total shrub utilization, the wood remains and can be splintered and used in the manufacture of pressed board materials or as fuel.

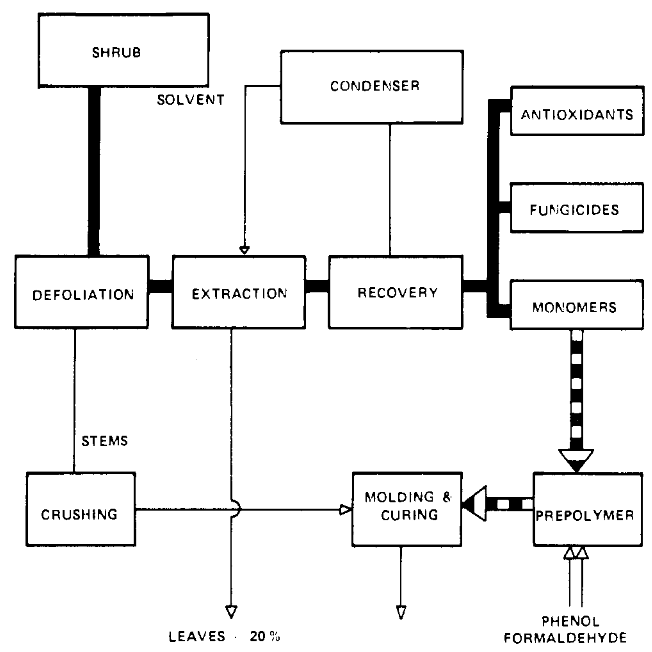

Figure 6. Flow diagram of the creosote bush process experimented at the pilot plant level at the present time in Mexico.

Pilot Plant. In 1978 pilot experiments (see Figure 6) on the extraction of the resin were begun at CIQA, with two goals: the determination of engineering data and semicommercialization of antioxidants; preliminary results were obtained at the end of 1978 and for the end of 1979 a general study including harvesting, transportation, engineering, market, and feasibility studies will be finished.

Candelilla (*Euphorbia antisyphilitica*). This resource has been used commercially for at least 50 years in Mexico, although the archaic methods used waste 50% of the wax (properties and composition are shown in Table XII) contained in the plant and produce a material which does not compare favorably with Carnauba wax. The

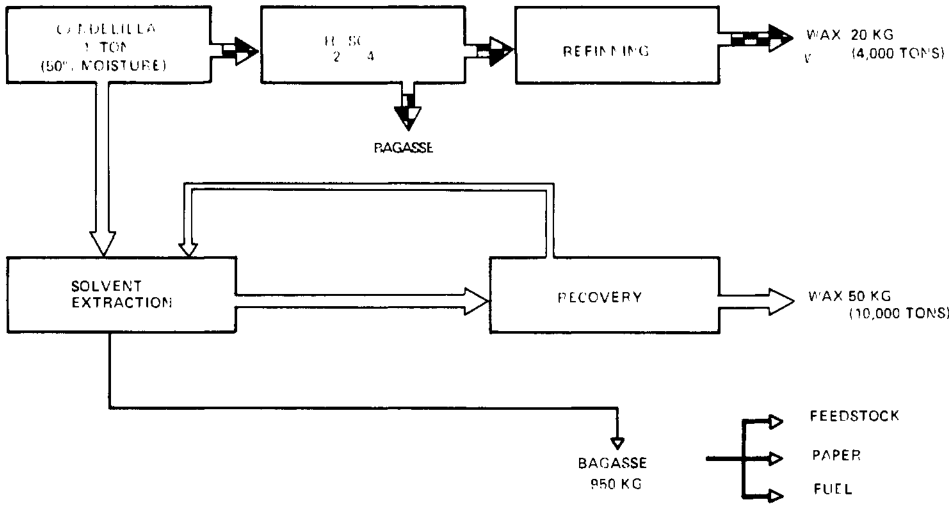

Figure 7. Candelilla extraction process experimented at the present time in Mexico. Upper part (H_2SO_4) represents the actual process and yields.

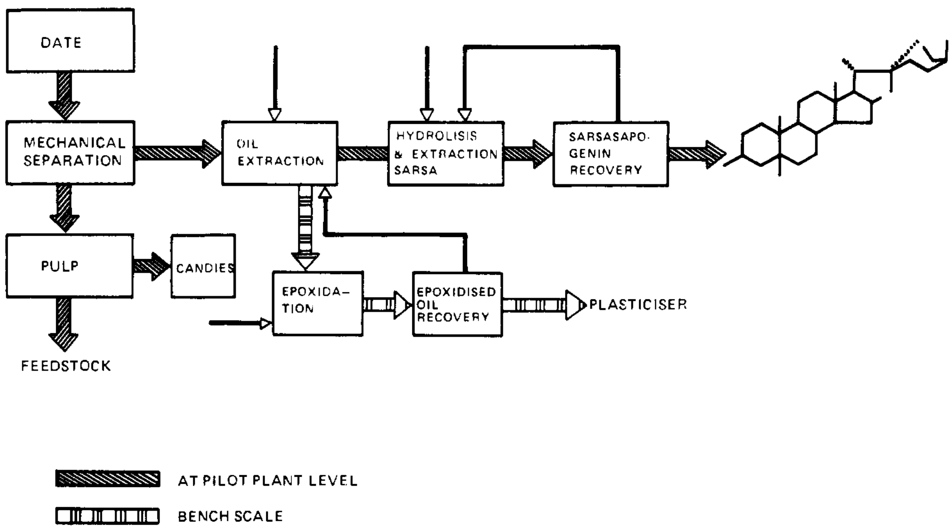

Figure 8. Yucca filifera process experimented at the pilot plant level in a joint project CONAZA–CONACYT. Pilot plant is located in Mexico City.

demand for candelilla has increased during the last 5 years, especially after the oil embargo. Present research is in the following areas.

Process Development. A way to generate new extraction systems is being sought, by using solvents (see Figure 7); results[76] obtained show that with this method twice as much wax can be obtained from the same quantity of plant. The physical appearance of the material also improves noticeably. It is hoped that engineering and feasibility results will be available at the end of 1979.

Product Development. Recently the Universidad Nacional Autōnoma de Mēxico (UNAM) developed Candelilla emulsions to treat citrus fruits[77] which is now being used on a commercial basis.

Cellulose Residues. Ninety-five percent of the material (dry basis) is cellulose residue, resin, etc., and could be used as fuel or to obtain biomass.

Government Involvement. The use of candelilla has been a permanent social problem, and it is hoped that the Mexican government will promote studies on the assessment of introducing modern technology, which would centralize production.

International. A bilateral project between Mexico and U.S. is also considered in the Bilateral Agreement on Science and Technology.

Chinese Palm (*Yucca filifera*). The date of this

Table XII. Candelilla Wax[78]

Composition	
ester of sitosterol and dihydroxymiricinoleic acid and other esters	29%
hydrocarbons (mostly hentriacontane and tritriacontane)	45%
free wax alcohols, lactones, and other resinous materials	26%
Properties	
melting point	65.5–72.5 °C
refractive index	14 550–14 611
specific gravity at 15%/4 °C	0.950–0.990
acidity index	12.0–22.0
saponification index	43–65
hydrocarbons	30.6–45.6%
fatty acids	20.6–29.0%
color: yellowish coffee	
flashpoint	235.4–248.5 °C
insoluble in a 50:50% mixture of xylene–toluene	0.0–0.1%
electric rigidity (velts per mm of section at 50 cycles using gloves of 25-mm diameter)	23 500–45 400

Yucca is produced during the first months of the year. The uses of the fruit are as follows.

Oil. The seed contains 20% oil (composition is shown in Table XIII), made up mainly of linoleic acid which,

Table XIII. Composition of Yucca Seed Oil

acid	%
linoleic	72
oleic	25
stearic	2
palmitic	1

besides being edible, can be epoxydized and used as a PVC plasticizer. Recent studies[47] show that its behavior is equivalent to commercial products of this type, and its effect on stability and migration are also comparable.

Sarsasaponin. The seed contains an average of 10% sarsasapogenin (hydrolized sarsasaponin) which could be an important source of steroidal material. Both the UNAM and CIQA are evaluating alternatives of chemical modifications which would promote its use in the pharmaceutical fields;[80] however a market study is required.

Pilot Plant. The CONAZA–CONACYT Program has a pilot plant for the obtention of sarsasaponin, sarsasapogenin and 16, β-dehydropregnenolone in Mexico City. A forecasted integral utilization process is shown in Figure 8.

Government Involvement. Apart from directly sponsoring this project, the Mexican Government will establish criteria for the use of this resource because the impact of Yucca used for similar purposes must be considered, as Mexico is one of the main producers of diosgenin (a competitive steroid) in the world.

Pulp. Using its high carbohydrate content different types of candy have been produced, and the pulp is also used as fodder.[79]

CONCLUSIONS

The search for renewable sources of organic raw materials is a world-wide phenomena and characteristic of the 1970's and as such is not an isolated fact but belongs to a general world crisis. At the same time humanity is confronted with the need to increase agricultural productivity and distribution, develop new sources of energy, and find substitutes for materials which in a relatively short period have become indispensable to man. The alternatives are numerous, due mainly to the great capacity of technological innovation that man has developed during the last 50 years. However, special care must be taken in the development of renewable resources, so that their use will promote the development of traditionally neglected regions. One solution in arid zones is the existing flora. In the Chihuahuan Desert plants have evolved with technical, market, and regional development possibilities to produce organic raw materials. A well-designed research and development model and social effort will convert them into characteristic dryland crops with industrial possibilities.

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Wood Extractives as Models for the Development of New Types of Pest Control Agents

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Molecular modification of obtusastyrene, a cinnamylphenol microbicide, and obtusaquinone, a *p*-quinone methide fish poison and marine borer larvicide, both of which occur in the durable timber, *Dalbergia retusa*, has led to the recognition of new structural types of insect control agents. A number of cinnamyl and benzyl derivatives of alkylphenols and 1,3-benzodioxoles have now been shown to be promising, highly effective sterilants for different fly species, mosquito growth inhibitors, beetle repellents, preservatives for wood in the marine environment, and, in some cases, toxicants for other insect pests. The most active benzylphenols are nonmutagenic in the Ames' test. Sterilant activity may be due to in vivo oxidation to reactive quinone methides.

Pesticide research in the agricultural industry generally continues to emphasize studies on the development and use of synthetic, broadly toxic compounds. However, health and environmental problems, and increasing insect resistance to many of these pesticides, clearly indicate that basic research must be directed to the discovery of new, safer types of pest control agents in order to insure high production and preservation of plant and animal agricultural products. Ideally, these new types of pest control agents should be active against a limited number of species, including specific target organisms, be biodegradable to nontoxic products, and be suitable for use in programs of integrated pest management.

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