BIOMASS FROM INTENSIVELY CULTURED PLANTATIONS AS AN ENERGY, CHEMICAL, AND NUTRITIONAL FEEDSTOCK[1]

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Abstract.--Several technologies are described that have been developed to convert wood to fuel, chemicals or food products. Biomass from intensively cultured plantations has potential as a source of material for these energy related technologies. The technologies discussed here include: pyrolysis, gasification, liquefaction, hydrolysis, chemicals from lignin and hemicelluloses, and conversion of wood and foliage to ruminant animal feedstocks. Although these technologies show great promise, most need to become more economically attractive before they can be used on a large scale.

INTRODUCTION

One of the most pressing problems of our century is that of producing enough energy to maintain our current standard of living. Many reports indicate that we could run short of inexpensive, easily obtainable, and easily transportable energy in the near future. In fact, the first two concerns are already being realized.

During the past 50 to 100 years most of our energy needs have been met using petroleum-derived products. Before that, coal supplied much of the energy for our industrial revolution, and before coal, wood was used for many centuries. Wood and charcoal still supply much of the energy needs of the people in many developing countries (King 1980). However, the recent industrial development of the technologically advanced countries has centered around petroleum and petrochemicals and the products derived from them. Shrinking domestic supplies and concern over the ability to obtain petroleum from other countries have added to the uncertainty in obtaining needed energy sources.

Although there are no easy solutions to the energy problem, several ways have been proposed to alleviate some of the difficulties. These include: 1) conservation of resources; 2) recycling certain materials (e.g. aluminum and paper); 3) development of more fuel efficient vehicles and industrial methods; and 4) developing alternative sources of energy (e.g. nuclear, biomass, solar, wind, etc.). In addition, novel ways of using our resources have been developed. These include: 1) renovating old technologies (i.e. windmills, ethyl alcohol production from biomass, improving home designs, etc.) and; 2) developing new technologies (i.e. solar panels, deriving hydrogen from water, etc.) to reduce our energy dependence on traditional sources.

Biomass grown in intensively cultured plantations is a potential source of raw material for some of the developing energy technologies. Short rotation, intensive culture (SRIC) systems are designed to capitalize on the rapid growth potential of selected woody species by using near optimal growing conditions (Dawson 1979). SRIC plantations could be located in close proximity to industrial firms. At the Rhinelander Forestry Sciences Laboratory, we have examined the raw material quality of and certain products made from SRIC biomass in an attempt to determine product suitabilities. Our studies to date on more conventional wood and wood fiber products have produced encouraging results.

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This paper focuses on several ways of using biomass (potentially from SRIC plantations) to produce fuels and chemicals so that substitutes for petroleum based fuels and chemicals may be found. In addition, research at Rhinelander and elsewhere on substituting wood and foliage for traditional animal feedstocks will be described. Although the conversion technologies described here are somewhat general, in that they apply to most lignocellulosic (or higher plant) material or residues, it is assumed that SRIC material will behave in a similar manner.

Producing fuels and chemicals from biomass combines old and new technologies. For example, as mentioned before, ethyl alcohol production as a fermentation product from plant material has been practiced for many years. Newer technologies are directed toward developing more efficient and less costly means of producing chemicals like ethyl alcohol from plant biomass.

The conversion technologies discussed in this paper include: 1) pyrolysis - the conversion of wood to produce charcoal, liquids and gases; 2) gasification - the production of gases and subsequently methyl alcohol via combustion; 3) liquefaction - the production of higher hydrocarbon liquids (oils); 4) the production of ethyl alcohol via hydrolysis; 5) the production of other chemicals for the chemical industries; and 6) the production of animal feedstocks from wood and foliage.

PYROLYSIS AND GASIFICATION

Pyrolysis and gasification are part of the continuum of the thermal combustion process (Soltes and Elder 1981). Pyrolysis (destructive distillation) is conducted at temperatures below 600°C, in the absence of oxygen (Brink 1976), and yields charcoal and a volatile phase (Goldstein 1980). The charcoal produced by this method is a home fuel source in many developing countries, a major source of recreational cooking fuel in the United States, and is used as a coking medium in steel manufacturing in Brazil. The volatile phase can be separated into condensible liquids (pyrolignous acid, wood tars, acetone, acetic acid, and methyl alcohol) and several noncondensible gases (carbon dioxide, carbon monoxide, hydrogen and methane) (Goldstein 1980). However, gas yields from pyrolysis are not as high as those obtained during gasification. Large amounts of methyl alcohol (or wood alcohol) and acetic acid were derived from the pyrolysis process during the early part of this century (Goheen 1981). Recent studies show that vacuum pyrolysis of wood at reduced pressures (300 to 400 mm Hg) may be an economical way of producing wood oils. These oils would then be upgraded to chemicals by extraction and/or processing, while the char could be used for fuel for gasification or direct combustion (Anon. 1982).

Gasification of biomass is done at higher temperatures than pyrolysis (over 600° C) in the presence of oxygen (Brink 1976). The compounds that are formed during gasification are primarily carbon monoxide and hydrogen (called producer gas), but other gases, such as carbon dioxide, methane, and water vapor are also produced (Brink 1981, Goldstein 1980). Producer gas (gasogen, or low Btu-gas) can be burned as is (e.g. in "wood-powered" vehicles) or it can be upgraded to a synthesis gas (containing only carbon monoxide and hydrogen) and then converted to ammonia, methyl alcohol or methane. The production of methyl alcohol via the gasification process has been considered to be one of the more promising methods of producing chemicals from biomass (Reed 1980, Williams 1980). According to Reed (1980), methanol can be formed by compressing synthesis gas to 50-200 atmospheres and passing it over a chromium or copper oxide catalyst at 250 to 350° C. Methanol can either be used as an octane enhancer to produce high-octane gasoline (Goldstein 1980, Lee et al. 1980), as a gasoline extender in mixture with petroleum, as a stand alone fuel, or used to produce methane for heating fuel. The Ford Motor Company is testing methanol as an automotive fuel in 40 of their cars and they have observed no apparent technical or conversion problems (Annon. 1981a). However, the primary detrimental aspect of using methanol as an automotive fuel is that it is corrosive to some engine parts (Ofoli and Stout 1980, Williams 1980).

Methanol is also currently used in the production of formaldehyde, solvents, acrylics, insecticides, fungicides, and textile fibers (Rowell and Hokanson 1979). It can be used to produce methane using catalytic convertors operating at high pressures (Rowell and Hokanson 1979). This process, however, is quite energy intensive and requires further technological development to be economically feasible (Cheremisinoff 1980).

LIQUEFACTION

Liquefaction is the thermochemical conversion of biomass to fuel oils. As mentioned earlier, methanol can be produced from synthesis gas. Methanol can then be converted to oil

using the Fisher-Tropsch (Goldstein 1980) or the Mobil processes (Lee et al. 1980). This approach is called "indirect" liquefaction (Reed 1980).

In most cases, however, liquefaction refers to the production of fuel oil (also known as heavy oil, "proto-oil", or "protoproduct") directly from plant biomass. Although Berl (1944) was primarily describing work on non-woody plants, he indicated that "protoproduct" (with a higher heating value of 14000-15000 Btu per pound) can be derived from any carbohydrate containing material. This "protoproduct" could be used as a substitute for fuel oil or, following treatment, as diesel fuel.

More recently, Appell (1977), Boocock and Mackay (1980), Cheremisinoff (1980), Reed (1980), Miller and Fellows (1981), Petter et al. (1981), and Livingston (1982) have studied liquefaction with encouraging results. In those studies, the wood was ground-up or shredded, mixed with water, and converted to oil using a catalyst (nickel or sodium carbonate), elevated temperatures (250 to 400°C), elevated pressures (1500 to 3500 psig), and an atmosphere rich in carbon monoxide (CO). Apparently the CO removed part of the oxygen from the wood carbohydrates. The oil produced had a Btu content of 13000 to 17000 Btu per pound (Appell 1977), compared to wood with a Btu content of about 8500 Btu per pound and heating oil with a Btu content of 18000 Btu per pound (Livingston 1982). Pepper et al. (1981) and Livingston (1982) published reports on the liquefaction of aspen while Boocock and Mackay (1980) published on the liquefaction of fast growing hybrid poplar trees. All studies obtained good results; e.g. Livingston (1982) reported a 35% to 45% conversion of the dry wood mass to oil. This recovery is equivalent to approximately one to two barrels of oil from each ton of wood. Unfortunately, production costs of $50.00 a barrel must be reduced considerably for the liquefaction process to be economically feasible at the present price of oil.

HYDROLYSIS

Pyrolysis and gasification processes are, by nature, rather non-selective processes for the conversion of wood to chemicals (Goldstein 1981a) in that the whole woody biomass is reduced in a single step. Processes such as hydrolysis are more selective in that the wood is separated into its three main components -- cellulose, hemicelluloses, and lignin during processing. Each component is, in turn, converted to useful chemicals (Goldstein 1981a), energy, and food (Lora and Wayman 1979).

One method that has been proposed for the separation procedure involves two steps (Seaman 1980, Lyons 1981). In the first step, hemicelluloses are removed using a dilute acid, warm alkali or steam pretreatment and the lignin is removed by solvents (e.g. cadoxen) (Lyons 1981). Cadoxen has also been shown to disrupt the crystalline structure to cellulose and make it more susceptible to hydrolysis (Ladisch et al. 1978). In the second step, the cellulose is hydrolyzed by either enzymes or acids. Hemicelluloses, if left in the solution, produce pentose sugars and acetic acid which interfere with product purity (Lyons 1981) and inhibit fermentation of sugars to ethanol (Cheremisinoff 1980). In addition, pretreatment enhances the susceptibility of the cellulose to further hydrolysis by either chemicals or enzymes (Zerbe 1980).

Other advantages of pretreatment are: 1) acceptable sugar yields (48% to 50%) and a high concentration of sugar (10% to 12%) can be obtained; 2) pentoses can be derived in the first stage and glucose in the second; 3) steam can be used or if acids are used, there is a low consumption of the acid; and 4) small digestors can be used due to the short time of hydrolyzation (Saeman 1980). Apparently the use of a steam pretreatment is species dependent because Lyons (1981) observed that steam pretreatment rendered poplar wood more susceptible to enzyme activity, but softwoods were rendered less susceptible.

Hydrolysis is the selective conversion of the carbohydrate components of wood to their constituent sugars (Goldstein 1980). It can be accomplished via several different methods. Autohydrolysis is actually a specialized form of pretreatment in that high pressure steam or a steam explosion process is used to separate hemicelluloses and lignin from cellulose. Hanselmann (1982) considered steam explosion of wood to be a very efficient separation process. Steam explosion yields cellulose, hemicelluloses that are partially hydrolyzed, and low molecular weight lignin compounds. The cellulose can then be digested by microorganisms to form ethanol (Hanselmann 1982). The hemicelluloses can be further processed to make furfural and xylitol, fermented to alcohol via microorganisms (Williams 1980), or used as a substrate for yeast production (Saeman 1980). The lignin that is obtained by this process is in a highly reactive form that can be extracted under relatively mild conditions (Lora and Wayman 1979).

Acid hydrolysis has been used successfully since the turn of the century. This process gained considerable attention during the World Wars when sources of petroleum were

under siege. Following W. W. II, interest in acid hydrolysis declined but interest has been renewed in the 1970's due to escalating oil prices.

In the acid hydrolysis process, either hydrochloric or sulfuric acid is used. Hydrochloric acid is used in concentrated form while sulfuric acid can be used in either dilute or concentrated forms. Concentrated acids allow hydrolysis to be conducted at lower temperatures than dilute acids and they give higher yields. However, concentrated acids require expensive, non-corrosive equipment and higher costs for acid recovery systems (Goldstein 1981a). Dilute acid hydrolysis is less corrosive but gives lower yields and requires higher operating temperatures (Goldstein 1981a). In addition, although lignin has little effect on acid hydrolysis (Saeman 1979, Goldstein 1980), it is often rendered insoluble and unreactive following acid hydrolysis (Lora and Wayman 1979). Acid hydrolysis is one of the older technologies for converting biomass to various chemicals (Bungay 1982) and has the advantage of being applicable to most species of wood.

Enzyme hydrolysis is a third method for reducing cellulose to glucose and subsequently to ethyl alcohol. The enzymes (cellulases) for this process are derived from improved strains of wood decaying fungi and bacteria. Fungal enzymes have shown much promise in this reduction process. One of the fungi most suitable for large scale conversion of cellulose to glucose is Trichoderma reesei, a mutant of T. virida (Goldstein 1981a). Another organism that produces enzymes to convert cellulose to glucose is Aspergillus (Lyons 1981). Some organisms that hydrolyze glucose to ethanol include a yeast of Saccharomyces (Wiegel 1982) and bacteria of Clostridium (Wiegel 1982) and Thermonospora spp. The yeast, Pachysolen tannophilus, directly converts xylose (from hemicelluloses) to ethanol (Anon. 1981b). Another yeast, Candida tropicalis, converts xylose to ethanol under aerobic conditions (Jeffries 1981).

Although enzyme hydrolysis has been shown to give higher yields of glucose than acid hydrolysis (Lyons 1981), there are several problems inherent in its use. Research is now focusing on solutions to these problems. One problem is that most enzymes function best in a rather narrow temperature range. Enzymes are also negatively influenced by the high degree of crystallinity of cellulose and the high lignin content usually found in wood (Goldstein 1980). At present, the costs of these enzymes is also prohibitive, but these costs are declining and they may be more attractive in the future (Bungay 1982). In addition, the reaction time for the enzyme hydrolysis process is much slower than acid hydrolysis (Goldstein 1981a).

Glucose derived from hydrolysis can be converted to ethyl alcohol via fermentation (Lyons 1981), and ethyl alcohol can be converted to ethylene or butadiene, both important industrial chemicals (Goldstein 1980). Glucose can also be converted to a food that may be consumed by man or animals; to a feedstock to make solvents, plastics or other chemicals currently made from petroleum; or converted to single cell protein to be used as a food supplement (Lyons 1981).

OTHER CHEMICALS FROM BIOMASS

All chemicals in the wood should be fully utilized to make chemical utilization of wood economically feasible (Goldstein 1975). The best way to do this, as discussed above, is to separate the wood into its three main chemical components -- cellulose, hemicelluloses, and lignin, and make products from each component. The utilization of cellulose, via hydrolysis, has already been discussed. Although cellulose can be useful in producing materials such as glucose, single cell protein, etc., possibly its major benefit will come in the production of ethyl alcohol. Ethyl alcohol is currently being used as a motor fuel in Brazil and in some states in the United States. Ethyl alcohol is also an important intermediate to industrial chemicals, primarily ethylene and butadiene as mentioned above (Goldstein 1981a). Ethylene, butadiene, and phenol (from lignin) are the major building blocks for the production of synthetic polymers (Goldstein 1975).

Other chemicals can also be derived from hemicelluloses and lignin. According to Thompson (1981), hardwoods are composed of approximately 24% lignin, 48% cellulose, 3% glucomannan and 22% xylan with approximately 3% miscellaneous polymeric compounds. However, softwoods have a slightly different chemical composition with 29% lignin, 43% cellulose, 17% glucomannan, 8% xylan, and, again, 3% miscellaneous polymeric compounds. Xylan and glucomannan are two of the most important hemicelluloses in wood. Note that the relative proportions of each are reversed in hardwoods and softwoods. Aspen and hybrid poplar have been shown to have lower lignin contents than those hardwoods described above. Aspen has a lignin content of 16% to 21% (Dickson et al.

1974, Panshin and de Zeeuw 1980, Hajny 1981) while Populus hybrids have been shown to have an average lignin content of 21% (Dickson et al. 1974).

Chemicals derived from xylose, the hydrolyzate of xylan, include: D-xylose - useful for making food additives, detergents, or polyurethane; xylitol - useful as a sweetner, humectant, and plastic plasticizer; and furfural - useful in plastics, solvents and other chemical products (Thompson 1981). However, demand for mannose-derived chemicals, the hydrolyzate of glucomannan, is currently low and will remain low unless their price becomes more competitive with corresponding glucose-derived chemicals (Thompson 1981).

Phenols and other aromatic compounds can be derived from lignin and then used in synthetic polymer chemistry (Goldstein 1975). These aromatic compounds are of particular commercial interest because of their high market value (Hanselmann 1982). In addition, vanillin is routinely obtained from lignin sulfonates in spent sulfite liquors via alkaline hydrolysis with lime and sodium carbonate under carefully controlled partial pressures of oxygen (Goheen 1981). Vanillin is used for food flavorings and in the perfume industries (Goheen 1981). Unfortunately, if all hemicelluloses were converted to furfural and all lignin to phenols, the chemical market may not, at the present time, be able to absorb the large quantities obtained (Goldstein 1981b). Therefore, new markets for furfural and phenol will have to be developed.

ANIMAL FEEDSTOCKS FROM WOOD AND FOLIAGE

Although wood is made up of carbohydrate material, carbohydrates are often inaccessible to organisms that can reduce them into readily usable forms of energy. As mentioned earlier, the major reasons for this are the high degree of crystallinity of the cellulose and the high amounts of lignin present in wood. The presence of lignin in wood has been particularly effective in reducing the digestibility of wood to ruminant microorganisms (Hajny 1981, Scott et al. 1969).

Most work to date on this topic has been concerned with digestibility trials using ruminant animals. These animals require large amounts of vegetable matter in their diets. Research is aimed at supplementing their diets with wood feedstocks to extend the grain resource base.

Wood can either be used as a roughage (non-nutritive) material or as an energy food for ruminant animals (Scott et al. 1969). Use of highly concentrated cattle feeds require the addition of certain amounts of roughage so that the animal can maintain good health. Baker et al. (1975) considered 5 to 15% screened sawdust to be a practical roughage quantity in beef cattle rations.

However, the use of wood as an energy food for ruminants requires that wood be rendered more digestible. Because there is a direct relationship between the in vitro digestibility of wood and the degree of lignification (Hajny 1981), delignification of woody biomass is essential for improving digestibility. Populus wood has been shown, in some cases, to be relatively digestible without delignification, presumably because of its low lignin content (Kamstra 1979). However, delignification processes have been shown to improve the digestibility of Populus wood as well (Mellenberger et al. 1971).

Hajny (1981) and Satter et al. (1981) described several methods to increase the digestibility of wood. These include: electron radiation; vibratory ball milling; treatment with anhydrous ammonia, gaseous sulfur dioxide, or dilute sodium hydroxide; and use of pulping residues. Electron radiation, vibratory ball milling, and treatment with anhydrous ammonia, or dilute sodium hydroxide have been shown to increase the digestibility of hardwoods, but have little effect on the digestibility of softwoods (Hajny 1981, Satter et al. 1981). However, the use of gaseous sulfur dioxide does not exhibit this species specificity. The use of pulp residues will vary depending on the species and the pulping processes used. In general, screen rejects and pulp fines have acceptable digestibilities for ruminants (Hajny 1981).

All methods, in one way or another, influence biomass digestibility to varying degrees and have varying costs associated with them. From the standpoint of SRIC material, however, the results of digestibility trials of aspen are encouraging. Populus hybrids would probably behave similarly.

Autohydrolysis has been quite successful in the defibration of low density hardwoods (i.e. aspen). An autohydrolysis process developed by STAKE Technology Ltd. has shown particular industrial potential for the production of cattle feed supplements from the cellulose of native aspen.

The use of wood feedstocks also requires the addition of protein and other nutrients (Satter et al. 1981) before they would become an acceptable dietary supplement. In addition, the preparation of animal feedstocks from wood may require cost reductions to be competitive.

Although the discussion thus far has centered around uses of woody material as a fuel, energy or nutritional material, another possible product from SRIC plantations is commercial foliage.

An analysis of the chemical composition of hand-picked foliage from Populus hybrid clones indicated that this material was high in protein and could be used as a high quality livestock feed supplement (Dickson and Larson 1977a, 1977b). As a result of these analyses, further research has been devoted to the mechanical separation of leaves and commercial foliage from hybrid poplar trees.

Two methods that have been examined to date are the Morbark commercial foliage separator and the vacuum airlift segregator (VAS) (Crist et al. 1979, Isebrands et al. 1979, Nelson 1982[3]). The VAS has vacuum settings which can be adjusted to separate wood, bark, and leaf material that is riding on a wire mesh conveyor belt. The VAS was developed by the Forestry Sciences Laboratory at Houghton, Michigan (Arola et al. 1976, Sturos 1978, Sturos and Dickson 1980). Digestibility trials of VAS separated commercial foliage have shown particular promise (Crist et al. 1979) especially when the VAS is adjusted for maximum leaf separation (Nelson 1982[3]). In addition to high digestibilities, the VAS commercial foliage is high in protein and could possibly be used as a low-cost protein supplement in ruminant animals (Nelson 1982[3]). Further analyses are being done, and the results are encouraging.

SUMMARY

Woody biomass and woody residues offer much potential as a source of material for fuel, chemical and nutritional feedstocks. These raw materials are readily available in large quantities in this country, they are renewable, and in the case of intensively cultured plantations, they can be cultivated in areas close to where they are needed to provide maximum return.

A great deal of research has been done on the technological aspects of converting biomass to these energy and food related products. Apparently many of the technical problems have been solved. However, what is currently needed are ways to make these technologies more economically attractive. Biomass grown in intensively cultured plantations offers a new and attractive source of material for these promising technologies.

[3]Nelson, N. D. 1982. Personal Communication.

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