BIOMASS PROPERTIES AND GASIFICATION BEHAVIOR OF YOUNG BLACK LOCUST[1]

Wayne A. Geyer

Professor
Division of Forestry

and

Walter P. Walawender

Professor
Department of Chemical Engineering

Kansas State University
Manhattan, KS 66506

(Received August 1993)

ABSTRACT

Biomass properties were determined to characterize young black locust as an energy source or fiber feedstock. Calorific value (4,505 cal/g) and wood specific gravity (0.55) of black locust stem and branches were similar to those of other hardwoods. Its fiber length was relatively short (0.96 mm). Ash content in the wood was 0.37%. Air-blown gasification of whole-tree black locust chips in a downdraft gasifier produced a low energy gas (5.2–5.6 MJ/m^3). Trials at dry chip rates of 94 and 123 kg/h produced an average gas-to-feed mass ratio of 2.4 and an average char yield of 3.6% of the dry wood fed. Oven-dry biomass yields were 9.4 t/ha annually at 7,000 tree/ha.

Keywords: Black locust, *Robinia pseudoacacia* L., wood energy, specific gravity, calorific value, fiber length, gasification, biomass yield.

INTRODUCTION

Woody biomass is a proven energy source, and its use has increased from 2.1% in 1970 to 3.5% in 1986 of the 76.6 quads of energy used annually in the United States (Skog 1990). There is an overall tendency for increased use of wood for energy for both environmental benefits and cost (Zerbe 1990). In the United States, about 17% of the estimated 18 billion cu ft of roundwood timber harvested is for fuelwood (Skog 1990), most of which is from hardwoods. With practices similar to those used in agriculture, intensively managed plantations of fast-growing trees could produce high fiber yields and could contribute to future alternative energy supplies.

In developing countries, where three-quarters of the wood is burned for cooking (Postel and Heise 1988), a severe wood shortage exists. Numerous tree species should be evaluated to determine their potential to overcome this challenge. Black locust (*Robinia pseudoacacia* L.) is one species that appears promising because it has many desirable wood quality and ecological characteristics: high energy content, adaptability to many climatic conditions, rapid rate of growth, and ability to fix nitrogen (Hanover 1992). This species has a broad naturalized range in the United States and is the most widely planted tree species in the world (Keresztesi 1988). It has wide adaptability and high potential importance as a fuelwood worldwide.

Although black locust is an important tree species for energy production and perhaps other technological uses, many basic properties of young trees have not been fully characterized,

[1] This is contribution 94-72-J, Kansas Agricultural Experiment Station, Kansas State University, Manhattan, KS.

thus limiting comparison to other woody plants and older trees.

The objective of this study was to establish baseline information characterizing young black locust as an energy or fiber feedstock and to provide limited empirical data on biomass yield data on upland sites in the Central Plains.

MATERIALS AND METHODS

Characterization studies

Planting site and measurement.—The study was conducted on an upland site in eastern Kansas having silt loam soil. A Nelder-wheel field design (Namkoong 1965) was replicated twice, providing five planting densities ranging from 1,400 to 7,000 trees per hectare with two border rings. Weeds were controlled for two years. A detailed description of this study has been published (Geyer et al. 1987).

Nondestructive annual measurements of height and diameter were used with individual tree weight curves (dormant) to determine dry weight area yields. These curves were developed from destructive sampling of 70 trees at similar spacings (Geyer 1993), giving the following equation:

$$\log_{10}(W) = 1.553 + 0.897 \log_{10}(D^2H), \quad (1)$$

where W is OVD tree weight (g), D is base diameter (cm), and H is total height (m). Individual tree weights, incorporating survival at seven years and planting density, were used to calculate yield.

Sampling

Ten sample trees were collected for characterization from randomly selected tree bundles (one tree per bundle) during the 1984–1985 dormant season from a recently harvested seven-year-old, short-rotation "energy plantation" growing adjacent to the Nelder-wheel growth plots. Also, disks were taken from 15 additional trees for determining wood specific gravity. Sample trees were chipped using a MORBARK EEGER BEAVER chipper and thoroughly mixed. Twenty random samples (about 0.5 kg) were taken from the chip pile for wood characterization.

Calorimetry.—The calorific value was determined for ground, oven-dried, whole-tree chips, according to ASTM STANDARD D 2015-77 (1981a). The material used for the evaluation was ground to pass through a 20-mesh screen to achieve complete combustion and good pellet cohesion (Neenan and Steinbeck 1979). Thirty samples, each consisting of approximately one gram of milled material, were pressed into pellets and combusted in a Parr 1341 adiabatic calorimeter. Correction factors for the formation of acids were not included in the gross heat of combustion calculations (Murphey and Cutter 1974; Barnes and Sinclair 1984). However, calorific values were corrected for moisture regained during storage.

Specific gravity.—Disks of 5-cm thickness were taken from 15 additional trees at base, DBH, and middle branch levels for analysis. The specific gravity was determined on the basis of oven-dry weight per green volume of an individual disk segment. Green volumes were obtained by soaking disk segments for 10 days in water until constant volume was achieved. Excess moisture was removed from the surface of the sample with a damp cloth, and each sample's water displacement (volume) was measured. The sample then was oven-dried to constant weight (3 to 4 days) at 104 C and weighed to determine the dry weight.

Ash content.—Ten samples of oven-dried, ground, whole-tree chips were ashed in a muffle furnace. The ash content was determined following the ashing procedure described in ASTM STANDARD D 1102-56 (1981b).

Fiber length.—Fiber length was determined using a method similar to that of Tsoumis (1968). Match-stick-size slivers taken from chips were placed in a solution of equal parts glacial acetic acid and hydrogen peroxide (30% volume) and heated in an oven at 60 C for 48 hours. Fibers then were separated, placed on slides, and projected onto a calibrated bullseye ring using a Mark VII micro-projector. Five fibers on each of 20 slides were measured and recorded.

Gasification studies

Chip source.—Approximately 1,500 kg of black locust chips for the gasification studies were obtained from additional 5-year-old trees with trunk diameters ranging from 5 to 15 cm. The trees were cut and stored outdoors for more than a year before they were chipped. The whole-tree chips were from stems and branches.

Chip chemical and physical properties.—A number of properties were determined for the whole-tree chips. These consisted of elemental analysis (ultimate analysis) of dry material (Perkin Elmer Model 2906 elemental analyzer); chemical constituents (cellulose, hemicellulose, and lignin) using neutral-detergent, acid-detergent fiber, and permanganate lignin methods as described by Goering and Van Soest (1970); moisture content; heating value (ASTM-D2015-66); average chip thickness; chip bulk voidage; chip bulk density; dry wood density (dry wood and dry volume); and wood internal voidage. Details of the measurement methodology have been given by Walawender et al. (1988).

Bulk voidage and bulk density are properties associated with an ensemble of chips and depend on the extent of packing. These properties were obtained for packing associated with dumping the chips into a container, i.e., loose packing. This condition is characteristic of the packing of chips in the top section of the gasifier.

The wood internal voidage was estimated from the following relationship:

$$\text{Wood Internal Voidage} = \\ = 1 - \frac{\text{Dry Wood Density}}{\text{Density of Wood Cell Material}} \qquad (2)$$

The density of wood cell material is relatively independent of tree species; it has a specific gravity of approximately 1.5 (Panshin and deZeeuw 1970).

Gasification.—Gasification studies were conducted with the Buck Rogers "Gasifire." A description of the air-blown downdraft gasifier along with the measurement and computational procedures have been given by Walawender et al. (1988). Two trials were conducted, one at a low fan rotation speed of 1,793 rpm and one at a high fan rotation speed of 2,560 rpm both with a grate rotation speed of 3 rph.

Direct measurements consisted of wet feed rate, char rate, gas composition, and condensate-to-dry gas ratio. Material balance procedures (Walawender et al. 1988) were used to determine dry air input rate, dry product gas rate, and water output rate.

Results were expressed in terms of mass ratios to dry feed, such as the air-to-feed and gas-to-feed ratios. Because char yield is typically small, it is expressed as a percentage of dry feed. Other results consisted of cold gas efficiency, mass conversion efficiency, and energy output rate. All of the above performance measures have been defined by Walawender et al. (1988).

RESULTS AND DISCUSSION

Wood properties

All of the wood properties determined are summarized in Table 1. The average calorific value of black locust wood was 4,505 calories per gram. This value is within the range for hardwoods quoted by Arola (1976), which varied from 3,886 cal/g for white ash to 5,728 cal/g for birch, but less than the 4,677 cal/g reported for black locust by Stringer (1992). Black locust's average heating value was 4.5% lower than the average of 4,722 cal/g reported for hardwoods by Panshin and deZeeuw (1970). However, it was slightly higher than the 4,476 cal/g reported for several Great Plains hardwood seedlings (Geyer 1981).

Black locust wood is usually moderately heavy, with a specific gravity (SG) of 0.69 (Stringer 1992). Our results based on oven-dry weight and green volume of disk samples were somewhat less, i.e., an average SG of only 0.58 for stem wood and 0.49 for branch wood.

TABLE 1. *Wood properties of 7-year-old black locust.*

Property	Mean	Minimum	Maximum	SD	Sample size
Calorific value (cal/g)	4,505	3,663	4,870	123	30
Ash content (% ash)	0.37	0.22	0.51	0.10	10
Fiber length (mm)	0.96	0.73	1.26	0.12	100
Specific gravity (gr. vol)					
Base[1]	0.59	0.51	0.64	0.05	15
DBH	0.57	0.51	0.64	0.04	15
Branches	0.49	0.40	0.64	0.07	15
Combined[2]	0.55	0.40	0.64	0.07	45

[1] Mean values between base, DBH, and branches differ significantly at the <1% level.
[2] Combined weighted average of above based on dry weight percentage.

Commercial North American hardwoods average 0.51 (Forest Products Laboratory 1987). Although the combined wood values had a specific gravity of 0.55, no significant differences were found between the two stem heights. Specific gravities of the base (0.59), DBH (0.57), and branch (0.49) samples differed significantly at the 1% level.

The ash content of black locust had a mean value of 0.37% based on oven-dry weight. Normally, ash content for wood of tree species ranges from 0.1 to 0.5% for wood (Panshin and deZeeuw 1970). Stringer (1992) reported ash contents ranging from 0.56 to 0.87 from the base to nearly the top of 10- to 12-year-old black locust trees.

The average fiber length of 0.96 mm for black locust in our study is shorter than the 1.05 mm reported by Stringer (1992) and shorter than the average length of 1.13 mm for North American hardwoods (Panshin and deZeeuw 1980). This difference may be an age effect, because our samples were from young trees.

Gasification studies

The chemical and physical properties of the whole-tree chips used for gasification are summarized in Table 2. Note that the wood density presented is on a dry weight and dry volume basis. The ash content of 1.61% and the heating value of 19.9 kJ/g (4,756 cal/g) are higher than the values given earlier for wood because of the presence of bark from both stems and branches in these chips. The cellulose content (50.94%) was relatively high and the lignin content (17.72%) relatively low for these young

TABLE 2. *Chemical and physical properties of whole-tree chips of young black locust.*

Elemental composition (dry %)*				
C	H	O	N	Ash
49.42	6.32	43.19	1.17	1.61

Chemical constituents (%)†		
Cellulose	Hemicellulose	Lignin
50.94	20.93	17.72

Heating value (kJ/g)†	Average chip thickness (cm)*
19.9	0.55
Chip bulk voidage†	Chip bulk density (kg/m^3)†
0.48	181
Dry wood density (kg/m^3)†	Wood internal voidage
730	0.51

* Mean values for 10 determinations.
† Mean values for 5 determinations.

TABLE 3. *Downdraft gasification results for whole treechips of young black locust.*

Run. no.	Wet feed rate (kg/h)	Moisture content (%-w.b.)	Dry feed rate (kg/h)	Air-to-feed ratio	Gas-to-feed ratio	Char yield (%)
5004	93.8	9.0	85.4	1.57	2.46	3.2
5008	123.1	8.0	113.3	1.41	2.32	4.0

Run no.	Mass conversion efficiency	Cold gas efficiency	Gas higher heating value (MJ/m^3)	Energy output rate (MJ/h)
5004	0.92	0.58	5.24	982
5008	0.93	0.59	5.61	1332

Run no.	Dry gas composition (%)			
	H_2	CO_2	N_2	CO
5004	12.8	12.6	46.7	27.1
5008	13.3	12.7	44.2	28.7

trees as compared to 40.9% and 30.1%, respectively, shown by Panshin and deZeeuw (1980) for mature trees.

The results from the gasification trials are summarized in Table 3. The grate rotation speed of 3 rph was found previously to be near optimal for the gasifier (Walawender et al. 1988). This is reflected by the relatively low char yield of 3–4%. The air-to-feed mass ratios for the two trials are somewhat less than the optimal range of 1.6 to 1.7. This reduces the gas-to-feed mass ratio. However, the gas has a relatively low nitrogen content, which, in turn, gives a larger gas heating value. An increase in the fan rotation speed increased the wood feed rate, which subsequently increases the energy output rate; this agrees with previously reported observations (Walawender et al. 1988). The energy output rate of the order of 1,000 MJ/h (1 million Btu/h) is suitable for small- to moderate-scale industrial operations.

Biomass yield

Planting density substantially affected all tree growth characteristics, except total height and survival (Table 4). Overall survival remained 90% after seven years. Annual oven-dry weight yields decreased with lower planting density. The lowest tree density (1,400 tree/ha) produced less than half the yield of the highest planting density (7,000 trees/ha). Because of the limited sample size, confidence intervals were calculated only for base diameter and yield at the widest and narrowest spacing. They did not overlap at "*t*" 0.05 value, thus indicating that the difference is significant. The mean annual increment (MAI) growth rate of dry wood at seven years was still increasing (16% greater than at four years), indicating that the biological harvest age had not been reached. Signs of locust borer (*Megacyllene robioniae*) attacks were present and might have limited growth. Average annual growth rates were greater than those previously reported for several younger-aged hardwood species in Kansas (Geyer 1981) and for young Siberian elm (*Ulmus pumila* L.) growing on the same site (Geyer et al. 1987).

TABLE 4. *Mean tree growth characteristics for plant density trials of 7-year-old black locust grown in eastern Kansas on upland loamy prairie soils.*

Tree density (no./ha)	Survival (%)	Total height (m)	Stump diameter @ 10 cm (cm)	Annual oven-dry yield of dormant material
7,000	98	7.1[1]	7.6[1]	9.4[1]
4,700	90	7.4	8.6	7.4
3,200	93	7.6	10.1	6.0
2,100	85	7.8	9.8	4.8
1,400	84	7.2	12.9	3.6

[1] The confidence intervals at the "t" 0.05 level for the lowest and highest two densities did not overlap, thus indicating a significant difference.

CONCLUSIONS

The data presented for young black locust show that: 1) tree wood properties are similar to those of other hardwoods, except calorific values are slightly lower, specific gravity is higher, ash is lower, and fiber length is shorter than most hardwoods, but lower than older black locust trees; 2) air-blown downdraft gasification can produce a low energy gas with a high mass conversion efficiency and a low char yield; and 3) this species can produce high biomass yields when grown in short-rotation forestry plantations; however, maximum biological growth rates had not yet been achieved at seven years, even at a close planting density of 7,000 trees/hectare.

REFERENCES

AMERICAN SOCIETY FOR TESTING MATERIALS 1981a. Standard test method for gross calorific value of solid fuel by the adiabatic bomb calorimeter. ASTM D 2015-77, Philadelphia, PA.

———. 1981b. Standard test method for ash in wood. ASTM D 1102-56, Philadelphia, PA.

AROLA, R. A. 1976. Wood fuels—How do they stack up? Forest Products Research Society Proc. (14), Madison, WI.

BARNES, D. P., AND S. A. SINCLAIR. 1984. Gross heat of combustion of living and spruce budworm-killed balsam fir. Wood Fiber Sci. 16(4):518–522.

FOREST PRODUCTS LABORATORY. 1987. Wood handbook: Wood as an engineering material. USDA Agric. Handbk. No. 72. 466 pp.

GEYER, W. A. 1981. Growth, yield, and woody biomass characteristics of seven short-rotation hardwoods. Wood Sci. 13(4):209–215.

———. 1993. Influence of environmental factors in woody biomass productivity in the Central Great Plains, USA. Biomass Bioenergy 4(5):333–337.

———, R. M. ARGENT, AND W. P. WALAWENDER. 1987. Biomass properties and gasification behavior of 7-year-old Siberian elm. Wood Fiber Sci. 19(2):176–182.

GOERING, H. K., AND P. J. VAN SOEST. 1970. Forage fiber analysis. USDA Agric. Handbk. No. 370, Agricultural Research Serv.

HANOVER, J. W. 1992. Black locust: An historical and future perspective. Proceedings, International Conf. on Black Locust: Biology, Culture, and Cultivation. Michigan State Univ., East Lansing, MI, June 17–21, 1991. 277 pp.

KERESZTESI, B. 1988. The black locust. H. Stillman Publishers, Inc., Boca Raton, FL. 196 pp.

MURPHEY, W. K., AND B. E. CUTTER. 1974. Gross heat of combustion of five hardwood species at differing moisture contents. Forest Prod. J. 24(2):44–45.

NAMKOONG, G. 1966. Application of Nelder's designs in tree improvement research. Pages 24–37 *in* Proceedings 8th South Conf. for Tree Improvement, Georgia Forest Res. Council, June 16–17, 1965. Savannah, GA.

NEENAN, M., AND K. STEINBECK. 1979. Caloric values for young sprouts of nine hardwood species. Forest Sci. 25(3):455–461.

PANSHIN, A. J., AND C. DEZEEUW. 1970. Textbook of wood technology, 3rd ed. McGraw-Hill, Inc., New York, NY. 722 pp.

———, AND ———. 1980. Textbook of wood technology, 4th ed. McGraw-Hill, Inc., New York, NY. 722 pp.

POSTEL, P., AND L. HEISE. 1988. Reforesting the earth. Worldwatch Inst. Rep. State of the World. 1988. L. R. Brown, New York/London. 237 pp.

SKOG, K. 1990. Fuelwood consumption. *In* Analysis of the timber situation in the United States: 1989–2040. USDA Forest Serv. Gen. Tech. Doc. RM-199. 226 pp.

STRINGER, J. W. 1992. Wood properties of black locust (*Robinia pseudoacacia*): Physical, mechanical, and quantitative chemical variability. Proceedings, International Conf. on Black Locust: Biology, Culture, and Cultivation. Michigan State Univ., East Lansing, MI, June 17–21, 1991. 277 pp.

TSOUMIS, G. 1968. Wood as raw material. Pergamon Press, London, England. 275 pp.

WALAWENDER, W. P., C. S. CHEE, AND L. T. FAN. 1988. Operating parameters influencing downdraft gasifier performance. Pages 411–445 *in* D. L. Klass, ed. Energy from biomass and wastes XI. Institute of Gas Technology, Chicago, IL.

ZERBE, J. J. 1990. Wood use for energy. *In* Analysis of the timber situation in the United States: 1989–2040. USDA Forest Serv. Gen. Tech. Doc. RM-199. 226 pp.