Thermochemical properties of biomass fuels

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An analysis of 62 kinds of biomass for heat value

Biomass cogeneration and small power systems contribute over 100 Megawatts of electric generating capacity in California, and development of the technology is occurring throughout the world. The first requirement in design of a biomass energy system is an analysis of the fuel to be used. Extensive information is available on wood fuels, but comprehensive data on other kinds of biomass have not been developed.

We conducted research to characterize the fuel properties of a wide range of biomass materials, taking samples from six categories: field crop residues, orchard prunings, vineyard prunings, food and fiber processing wastes, forest residues, and energy crops. We analyzed 62 kinds of biomass for heating value and proximate chemical composition, and also analyzed 51 of those for ultimate elemental composition. All analyses were performed in ac-

TABLE 1. Chemical analysis of biomass fuels

			Proximate analysis			Ultimate analysis						
	Qvh	Qvl	VCM	ASH	FC	C	H	O	N	S	Cl	Residue
	MJ/kg	*MJ/kg*	*% by weight d.b.*			*% by weight d.b.*						
Field crops												
Alfalfa seed straw	18.45	17.36	72.60	7.25	20.15	46.76	5.40	40.72	1.00	0.02	0.03	6.07
Barley straw	17.31	16.24	68.80	10.30	20.90	39.92	5.27	43.81	1.25			9.75
Bean straw	17.46	16.32	75.30	5.93	18.77	42.97	5.59	44.93	0.83	0.01	0.13	5.54
Corncobs	18.77	17.58	80.10	1.36	18.54	46.58	5.87	45.46	0.47	0.01	0.21	1.40
Corn stover	17.65	16.52	75.17	5.58	19.25	43.65	5.56	43.31	0.61	0.01	0.60	6.26
Cotton stalks	15.83	14.79	65.40	17.30	17.30	39.47	5.07	39.14	1.20	0.02		15.10
Rice straw (fall)*	16.28	15.34	69.33	13.42	17.25	41.78	4.63	36.57	0.70	0.08	0.34	15.90
Rice straw (weathered)†	14.56	13.76	62.31	24.36	13.33	34.60	3.93	35.38	0.93	0.16		25.00
Safflower straw	19.23	18.10	77.05	4.65	18.30	41.71	5.54	46.58	0.62			5.55
Wheat straw	17.51	16.49	71.30	8.90	19.80	43.20	5.00	39.40	0.61	0.11	0.28	11.40
Orchard prunings												
Almond prunings	20.01	18.93	76.83	1.63	21.54	51.30	5.29	40.90	0.66	0.01	0.04	1.80
Black walnut	19.83	18.65	80.69	0.78	18.53	49.80	5.82	43.25	0.22	0.01	0.05	0.85
English walnut	19.63	18.49	80.82	1.08	18.10	49.72	5.63	43.14	0.37	0.01	0.06	1.07
Vineyard prunings												
Cabernet Sauvignon	19.03	17.84	78.63	2.17	19.20	46.59	5.85	43.90	0.83	0.04	0.08	2.71
Cardinal	19.21		78.17	2.22	19.61							
Chenin blanc	19.13	17.94	77.28	2.51	20.21	48.02	5.89	41.93	0.86	0.07	0.10	3.13
Gewurztraminer	19.16		77.27	2.47	20.26							
Merlot	18.84		77.47	3.04	19.49							
Pinot noir	19.05	17.86	76.83	2.71	20.46	47.14	5.82	43.03	0.86	0.01	0.13	3.01
Ribier	19.12		76.97	3.03	20.00							
Thompson Seedless	19.35	18.18	77.39	2.25	20.36	47.35	5.77	43.32	0.77	0.01	0.07	2.71
Tokay	19.31	18.12	76.53	2.45	21.02	47.77	5.82	42.63	0.75	0.03	0.07	2.93
Zinfandel	19.06		76.99	3.04	19.49							
Energy crops												
Eucalyptus												
camaldulensis	19.42	18.23	81.42	0.76	17.82	49.00	5.87	43.97	0.30	0.01	0.13	0.72
globulus	19.23	18.03	81.60	1.10	17.30	48.18	5.92	44.18	0.39	0.01	0.20	1.12
grandis	19.35	18.15	82.55	0.52	16.93	48.33	5.89	45.13	0.15	0.01	0.08	0.41
Casuarina	19.44	18.26	78.94	1.40	19.66	48.61	5.83	43.36	0.59	0.02	0.16	1.43
Cattails	17.81	16.31	71.57	7.90	20.53	42.99	5.25	42.47	0.74	0.04	0.38	8.13
Poplar	19.38	18.19	82.32	1.33	16.35	48.45	5.85	43.69	0.47	0.01	0.10	1.43
Sudan grass	17.39	16.31	72.75	8.65	18.60	44.58	5.35	39.18	1.21	0.08	0.13	9.47

NOTES: For explanation of headings, see text. Data not determined where blanks occur in table. Values of 0.01 for S and Cl are at or below the detectable limit.
* Sample collected immediately after normal harvest of rice in the fall.
† Straw left in the field over winter and sample collected the following spring.

cordance with American Society for Testing and Materials (ASTM) standard methods.

The tables include the higher and lower heating values (Qvh and Qvl, respectively), as well as proximate and ultimate compositions. The proximate analysis yields the weight fractions of volatiles (VCM), ash (ASH), and fixed carbon (FC). The ultimate analysis yields the weight fractions of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and chlorine (Cl). The values for residue under the ultimate analyses represent the undetermined fraction of the biomass, which is essentially ash. The percentages of ASH from the proximate analyses and of residue from the ultimate analyses are not the same, because two different analytical techniques were used, but the values are relatively close over the range of ash contents determined. All data in the tables are reported on a dry basis (zero moisture).

We determined the higher heating value by burning a finely ground and pelleted sample of the fuel in oxygen. Qvh is the constant volume heating value. Most biomass combustion and gasification systems operate at close to constant pressure rather than constant volume. The constant pressure heating value can be computed from the constant volume value but, since the correction is small, it can usually be omitted.

The lower heating value was calculated from the higher heating value and the concentration of hydrogen in the fuel at zero moisture. Water, one product of biomass combustion, is formed from the hydrogen in the fuel. The ultimate elemental analysis indicates the concentration of hydrogen, in addition to the other elements.

The formation of water is important, because it can leave the system as either vapor or liquid. The higher heating value is determined for water in the liquid phase, the lower heating value for water in the vapor phase. The lower heating value is less than the higher value by the latent energy of water vaporization. Water is seldom condensed in practical combustion systems, but the thermal efficiency of such systems is often reported on the basis of the higher heating value. Moisture in the fuel will reduce both heating values, because there is less dry matter per unit weight of moist fuel. The lower heating value is also reduced because of the additional energy used to vaporize the

TABLE 2. Chemical analysis of biomass fuels

			Proximate analysis			Ultimate analysis						
	Qvh	Qvl	VCM	ASH	FC	C	H	O	N	S	Cl	Residue
	MJ/kg	*MJ/kg*	*% by weight d.b.*			*% by weight d.b.*						
Forest residue												
Black locust	19.71	18.55	80.94	0.80	18.26	50.73	5.71	41.93	0.57	0.01	0.08	0.97
Chaparral	18.61	17.58	75.19	6.13	18.68	46.90	5.08	40.17	0.54	0.03	0.02	7.26
Madrone	19.41	18.20	82.99	0.57	16.44	48.00	5.96	44.95	0.06	0.02	0.01	1.00
Manzanita	19.30	18.09	81.29	0.82	17.89	48.18	5.94	44.68	0.17	0.02	0.01	1.00
Ponderosa pine	20.02	18.8	82.54	0.29	17.17	49.25	5.99	44.36	0.06	0.03	0.01	0.30
Tanoak	18.93	17.73	80.93	1.67	17.40	47.81	5.93	44.12	0.12	0.01	0.01	2.00
Tanoak, bark	18.40		73.11	3.49	23.40							
Tanoak, sapwood	19.07		83.61	1.03	15.36							
Redwood	20.72	19.51	79.72	0.36	19.92	50.64	5.98	42.88	0.05	0.03	0.02	0.40
Redwood, bark	19.58		68.44	1.60	29.96							
Redwood, sapwood	20.31		80.12	0.67	19.21							
Redwood, heartwood	21.14		80.28	0.17	19.55							
Redwood, mill wastes	20.98		81.19	0.18	18.63							
White fir	19.95	18.74	83.17	0.25	16.58	49.00	5.98	44.75	0.05	0.01	0.01	0.20
White oak	19.42	18.33	81.28	1.52	17.20	49.48	5.38	43.13	0.35	0.01	0.04	1.61
Food and fiber processing wastes												
Almond hulls	18.22	17.13	71.33	5.78	22.89	45.79	5.36	40.60	0.96	0.01	0.08	7.20
Almond shells	19.38	18.17	73.45	4.81	21.74	44.98	5.97	42.27	1.16	0.02		5.60
Babassu husks	19.92	18.83	79.71	1.59	18.70	50.31	5.37	42.29	0.26	0.04		1.73
Sugarcane bagasse	17.33	16.24	73.78	11.27	14.95	44.80	5.35	39.55	0.38	0.01	0.12	9.79
Coconut fiber dust	20.05	19.02	66.58	3.72	29.70	50.29	5.05	39.63	0.45	0.16	0.28	4.14
Cocoa hulls	19.04	17.97	67.95	8.25	23.80	48.23	5.23	33.19	2.98	0.12		10.25
Cotton gin trash	16.42	15.35	67.30	17.60	15.10	39.59	5.26	36.38	2.09			16.68
Grape pomace	20.34	19.14	68.54	9.48	21.98	52.91	5.93	30.41	1.86	0.03	0.05	8.81
Macadamia shells	21.01	20.00	75.92	0.40	23.68	54.41	4.99	39.69	0.36	0.01		0.56
Olive pits	21.39	20.12	78.65	3.16	18.19	48.81	6.23	43.48	0.36	0.02		1.10
Peach pits	20.82	19.62	79.12	1.03	19.85	53.00	5.90	39.14	0.32	0.05		1.59
Peanut hulls	18.64	17.53	73.02	5.89	21.09	45.77	5.46	39.56	1.63	0.12		7.46
Pistachio shells	19.26	18.06	82.03	1.13	16.84	48.79	5.91	43.41	0.56	0.01	0.04	1.28
Prune pits	23.28	22.08	76.99	0.50	22.51	49.73	5.90	43.57	0.32			0.48
Rice hulls	16.14	15.27	65.47	17.86	16.67	40.96	4.30	35.86	0.40	0.02	0.12	18.34
Walnut shells	20.18	19.02	78.28	0.56	21.16	49.98	5.71	43.35	0.21	0.01	0.03	0.71
Wheat dust	16.20	15.16	69.85	13.68	16.47	41.38	5.10	35.19	3.04	0.19		15.10

fuel moisture. The heating values at any moisture content can be found from:

$$QhM = Qh0\,[1\text{-}M]$$

$$QlM = [1\text{-}M]\,[Qh0 - \lambda\,(\frac{M}{1\text{-}M} + 0.09H)]$$

M = moisture content wet basis (decimal)
QhM = higher heating value at moisture content M
QlM = lower heating value at moisture content M
Qh0 = higher heating value at zero moisture (see tables)
λ = latent energy of water vaporization
H = concentration of hydrogen in the fuel (% by weight dry basis — see tables)

Higher heating values for the samples analyzed range from 14.56 to 23.28 megajoules per kilogram (MJ/kg) dry basis. Heating values are proportional to volatile concentration and inversely proportional to ash content. When higher heating value is expressed on a dry, ash-free basis, the difference between the maximum and minimum values is only 4.84 MJ/kg. Many of the field crop residues and food and fiber processing wastes had high ash contents.

Biomass has high volatile and high oxygen concentrations compared with fossil fuels. The high oxygen results from the lignocellulosic structure of plant tissues and is the principal reason for the low heating values of biomass as compared with hydrocarbon fuels. Nitrogen concentrations are high in field crop residues, vineyard prunings, and nut hulls. Fuel-bound nitrogen is an important contributor to nitrous oxide (NOx) emissions from biomass combustion systems. All fuels analyzed had low sulfur concentrations.

The values in the tables reflect the intrinsic properties of the fuels as much as possible. We performed the sampling so as to minimize added dirt. The dirt content varies substantially in materials like cotton gin trash, and no single value for ash can describe all possible sources of the fuel. The type of system used to collect and handle the fuel may affect the amount of added dirt and the ash content. Added dirt may also change the ash composition, resulting in increased potential for slag formation. Data in the tables can be used for preliminary design but cannot be substituted for a complete analysis of the intended fuel in making a detailed design.

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A profile of California farmworkers

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Melon harvest crew in Imperial Valley.

Recent debates on immigration reform have generated contradictory statements about California's farmworkers. Some advocates of a legal guestworker program contend that most seasonal farmworkers are illegal/undocumented workers who would abandon agriculture for nonfarm jobs if offered an amnesty. Other observers counter that many U.S. citizens and legal immigrants also do seasonal farm work, and that modern personnel practices could attract and retain more such workers.

In August 1983, the University of California and the California Employment Development Department interviewed 1,286 farmworkers throughout the state in an effort to establish an up-to-date profile. Each of EDD's 42 farmworker offices interviewed 30 workers, selected in a manner to reflect the approximate number and characteristics of fieldworkers involved in each office area's agriculture (detailed survey methodology will be published in a forthcoming Giannini Foundation Information Report). The UC-EDD sample provided the most comprehensive picture of farmworkers since a 1965 California Farmworker Profile requested by the state legislature.

Farmworker characteristics

Most of the 1,286 farmworkers surveyed in 1983 were immigrants: 80 percent were persons born abroad who later entered the United States. Most of these immigrants — 73 percent — were born and raised in Mexico. U.S.-born farmworkers (20 percent) and those born in other countries (7 percent) composed the rest of the sample.

Most of the immigrants had greencards (work and residence documents issued by the U.S. Immigration and Naturalization Service), which entitled them to work legally in the United States. The validity of these greencards was not established by interviewers, so the legal status estimates presented here are minimums. Fully two-thirds of the 1,028 immigrant farmworkers interviewed had greencards, 25 percent were clearly illegal or undocumented, and 5 percent had their legal status pending. Many families headed by legal or undocumented immigrant adults included U.S. citizen children.

A disproportionate number of illegals were young men, and the arduous harvesting tasks employing young men in citrus, grapes, and tree fruits had work forces that were 30 to 50 percent illegal. Illegal workers were not distributed uniformly around the state; the coastal vegetable areas had fewer illegals than the Central Valley.

Farmworkers had a household size distribution unlike the general work force in California. One-third of the adults interviewed lived alone, another third lived in households with five or more members.