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Wood and Wood-based Residues in Animal Feeds

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Cellulose is the most abundant, naturally renewable material on earth. It, and hemicellulose, make up about 70% of the dry weight of shrubs and trees. The cellulose of woody plants, however, is largely unavailable to ruminants because of the highly crystalline nature of the cellulose molecule and the existence of a lignin-carbohydrate complex. If convenient ways can be found to enhance the availability of wood cellulose to enzymatic or microbiological systems, wood residues could provide an additional renewable energy feed supply for a world that can maintain no contingency reserve of feedstuffs. It would permit utilization of the large quantities of cellulosic residues that occur during harvest and manufacture of wood and cellulose products and provide a method of disposal of the used products.

This article presents a summary of research conducted on the use of wood and wood-based materials in animal feeds at the Forest Products Laboratory and the University of Wisconsin, and research in cooperation with the Tennessee Valley Authority, the U.S.D.A. Agricultural Research Service, Animal Nutrition Laboratory, Pennsylvania State University, and Auburn University.

Animal Feeding Studies

Early Research. Efforts by the Forest Products Laboratory to utilize wood in animal feeds began in 1920 when eastern white pine and Douglas-fir sawdust were hydrolyzed and fed to animals at the University of Wisconsin and the U.S. Department of Agriculture, Beltsville, Md. The work was started as a result of high feed grain prices during 1918-19. Wood was hydrolyzed and the washings and hydrolyzate were neutralized, concentrated, mixed with the unhydrolyzed residue and dried (1).

[1] Forest Service, U.S. Department of Agriculture. Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

This type of material was used in several feeding experiments with sheep and dairy cows (2-4). Results indicated that certain animals could eat rations containing up to one-third hydrolyzed sawdust mixture. Animals requiring considerable energy intake such as dairy cows could eat up to 15% of the hydrolyzed mixture without noticeable milk production effects. It was determined that the eastern white pine mixture was 46% digestible and that the Douglas-fir mixture was 33% digestible. It was concluded that feeding hydrolyzed wood was practical only when natural feed grains were in short supply.

Research on wood hydrolysis was conducted in the 1940's to produce concentrated sugar solutions suitable for stock and poultry feed. Over 200 tons of molasses were produced in pilot plants and sent to universities, agricultural experiment stations, and other agencies for feeding tests with milk cows, beef cattle, calves, lambs, pigs, and poultry (5,6). In general, the tests indicated that wood-sugar molasses is a highly digestible carbohydrate feed comparable to blackstrap molasses. In addition, the protein value of torula yeast, grown on neutralized dilute wood hydrolyzate, was found to be equivalent to casein when supplemented with methionine (7). Torula yeast has also been produced in three North American plants on the residual sugars in spent sulfite pulping liquors. Two plants are now operating.

Results from feeding tests with wood molasses led to production during the early 1960's of a concentrated hemicellulose extract called Masonex, a byproduct from hardboard production by the Masonite Corporation (8).

Current Studies. Recent research on the use of wood and wood residue in animal feeds was started as one approach to utilize the vast quantities of residue from logging, lumber and plywood manufacturing, and pulp and papermaking. Wood residue may serve as a source of digestible energy or as a roughage in ruminant rations. Fattening feedlot cattle, as well as lactating dairy cattle, need a minimum of fibrous feed in their ration and it is conceivable that indigestible fibrous wood residues could play a non-nutritive role in ruminant nutrition. It has been estimated that all of the wood and bark residues would supply more than enough roughage for all concentrates fed in the United States (9). In addition, more than 1.7 million tons of partially digestible pulp and papermaking fiber residues are produced annually that could supplement feed grains as sources of energy.

Animal feeding studies were conducted to determine acceptability, palatability, and digestibility of wood and bark residues to determine their value as roughage substitutes. Various physical and chemical methods to increase cellulose availability to rumen micro-organisms were evaluated with *in vitro* rumen methods. Digestibility trials were then conducted to determine the in vivo digestibility of products from selected treatments. Pulp and papermill fiber residues were also evaluated by chemical analysis, in vitro and in vivo methods. Rations containing as much as 80% fiber residues were fed to animals through a complete reproductive cycle to determine long-term effects on general health and reproductive capacity.

In Vitro Assay Methods. The dry matter digestibility of various wood species and of the effects of chemical and physical pretreatments on digestibility was determined by the in vitro rumen method of Mellenberger, et al. (11). Results are reported as percent weight loss after 5 days of incubation at 39° C. An enzyme method was developed to provide an alternative assay procedure that did not depend upon the availability of a rumen fistulated cow (12). This method utilizes "Onazuka" SS enzyme obtained from Trichoderma veride in an acetate buffer and usually a 10-day incubation period. Digestibility is determined by analyzing the solution before and after incubation to determine the increase in reducing substances. The results of this test do not directly indicate rumen digestibility but they do indicate changes in digestibility.

The in vitro rumen test indicated that the digestibility of all wood species is low (13,11). All softwoods or coniferous species are essentially nondigestible. Hardwoods, or deciduous species, are somewhat digestible. Digestibility of the wood and bark of several tree species is shown in Table I. Note that the digestibility of soft maple wood is about 20%, aspen wood is about 33%, and aspen bark is about 50%.

Figure 1 shows results of feeding trials with red oak wood (14) and aspen wood and bark (15) and a method for estimating the in vivo digestibility by extrapolation of the data to 100% wood or bark. The red oak trial was with sheep, and the aspen wood and bark trial was with goats. Thus for red oak, the estimated in vivo digestibility is 0%; for aspen wood it is estimated to be about 40%, and for aspen bark it is about 50%. This indicates that aspen wood and bark could supply considerable digestible energy as well as roughage for ruminants.

Wood Residues as an Alternate Source of Roughage. Even though most untreated woods can contribute little to the dietary energy needs of ruminants, wood can still serve a useful function as a roughage substitute. Roughage is required in the ration to provide tactile stimulation of the rumen walls and to promote cud-chewing, which in turn increases salivation and supply of buffer for maintenance of rumen pH. Roughage materials currently used include hay, corn cobs, cottonseed hulls, oat hulls, rice hulls, and polyethylene pellets. A roughage substitute should be: readily obtained at low cost, effective at low levels, uniform in chemical and physical characteristics, capable of easy and uniform

Table I

in vitro Dry-Matter Digestibility of Various Woods and Their Barks

Substrate	Digestibility[a] Wood	Digestibility[a] Bark	Substrate	Digestibility[a] Wood	Digestibility[a] Bark
	%	%		%	%
HARDWOODS			HARDWOODS--continued		
Red alder	2	--	Soft maple small twigs	37	--
Trembling aspen	33	50	Sugar maple	7	14
Trembling aspen (groundwood fiber)	37	--	Red oak	3	--
Bigtooth aspen	31	--	White oak	4	--
Black ash	17	45	SOFTWOODS		
American basswood	5	25			
Yellow birch	6	16	Douglas-fir	5	--
White birch	8	--	Western hemlock	0	--
Eastern cottonwood	4	--	Western larch	3	7
American elm	8	27	Lodgepole pine	0	--
Sweetgum	2	--	Ponderosa pine	4	--
Shagbark hickory	5	--	Slash pine	0	--
Soft maple	20	--	Redwood	3	--
Soft maple buds	36	--	Sitka spruce	1	--
			White spruce	0	--

[a]For comparison: Digestibility of cotton linters was 90%; of alfalfa, 61%.

mixing, maintain normal rumen functions and feed intake, and able to prevent rumen parakeratosis and liver abscesses (16). If it is used in dairy rations, it should maintain normal milk fat test.

The roughage qualities of red oak sawdust have been determined by feeding beef cattle and sheep (17-19). In addition to the usual criteria of weight gain and efficiency of feed conversion, such measurements of carcass quality as grade, rib-eye area, and fat marbling were also noted. Attention was focused on livers and stomachs at slaughter, because abnormalities in these organs are characteristic of animals on roughage-deficient diets. It was concluded that oak sawdust was an effective roughage substitute when used as 5 to 15% of the total ration.

Roughage is necessary in dairy cow rations to prevent abnormally low milk fat tests (20). For economic reasons it is desirable to produce milk of high fat content. Hay supplies are, at times, limited and costly in some areas. In these areas it would be desirable to have an alternate roughage that would meet the "roughage requirement" for lactating dairy cows, that is not seasonal and would be compatible with automated feeding systems. Aspen sawdust, which is about 35% digestible, was fed at various concentrations to lactating dairy cows to determine if part or all of the hay could be replaced when feeding high-grain rations.

One feeding experiment (21) with lactating cows shows that aspen sawdust was effective as a partial roughage substitute in a high-grain dairy ration. The aspen sawdust was air-dried and hammermilled to pass through a screen plate with 1/8-inch-diameter holes. Cows maintained a normal milk fat level on 2.3 kg. of hay and about 17 kg. of pelleted grain, one-third of which was aspen sawdust. Cows receiving a similar ration without sawdust had a milk fat content half as great. The ratio of ruminal acetate to propionate was much higher in the cows fed aspen. Inclusion of aspen in a high-concentrate ration nearly doubled ruminating time. If less dietary aspen would be equally as effective in complete pelleted dairy rations, aspen sawdust could become an attractive roughage substitute in areas where hay is expensive and difficult to obtain.

In a second experiment (22), combining various levels of aspen sawdust with 5% bentonite and 2% sodium bicarbonate (based on the total ration), it was found that aspen sawdust could be a roughage extender or a partial roughage substitute in high-concentrate dairy rations. Sawdust maintained fat test and diminished off-feed problems when constituting about 30% of the ration dry matter in high or all-concentrate dairy rations. Since the dry matter digestibility of aspen sawdust was less than for other ration components, cows eating sawdust-containing rations compensated for the lower digestibility by eating more of the ration; thus, cows maintained total digestible energy intake. Whether high-producing cows already at maximum feed intake could do this is questionable.

Aspen sawdust has useful roughage characteristics, but using it as the only roughage in high-concentrate dairy rations cannot be recommended. Approximately 30% of the ration dry matter would have to be sawdust; that is too high to be practical because the cows would have trouble consuming that large a volume of feed. Sodium bentonite and sodium bicarbonate apparently have an additive effect toward maintaining fat test when combined with aspen sawdust. In combination with bentonite and bicarbonate, smaller quantities of sawdust would probably be sufficient to maintain a given fat content of milk.

As little as 2.3 kg. of hay/cow per day is effective in stabilizing feed intake. To supplement the hay, adding 10-15% of the high-concentrate diet as aspen sawdust, 5% as sodium bentonite, and 2% as sodium bicarbonate might extend limited forage supplies. Since aspen sawdust does not serve well as the sole source of roughage in a complete all-concentrate ration, its potential appeal as a forage substitute for lactating dairy cows is reduced.

Pretreatments to Increase Digestibility

Several physical and chemical pretreatments were tested for their ability to increase digestibility of wood cellulose. The treatments were electron irradiation, vibratory ball milling, gaseous and liquid ammonia, gaseous sulfur dioxide, dilute sodium hydroxide, and white-rot fungi (23-25). Each of the treatments is capable of producing a product at high yield without a waste stream or byproduct.

The digestibility response to the various treatment conditions was followed by *in vitro* rumen and cellulase digestion assay procedures. Larger quantities of products of selected treatments were prepared for animal digestion trials with goats to determine *in vivo* digestibility and to observe palatability and acceptability. Goats were selected because they are small ruminants and require less space and feed.

High-Energy Electron Irradiation. The effect of exposure to increasing levels of electron irradiation on the *in vitro* digestibility of aspen and spruce is shown in Table II. Aspen carbohydrate digestion is essentially complete if it is assumed that only carbohydrate has been solubilized at an electron dosage of 10^8 rep. (roentgen equivalent physical). However, the lignin content of this aspen was 19.5%, and it might be expected that some lignin degradation products would be formed at this dosage level. If water soluble, these would contribute to the figure for dry matter digestibility. In any event, electron irradiation is an effective means for enhancing the digestibility

Table II

Effect of Electron Irradiation on *in vitro*

Rumen Digestibility of Aspen and Spruce

Radiation dosage	Digestibility	
	Aspen[a]	Spruce
rep.[b]	%	%
0	55	3
10^6	52	3
10^7	59	5
5×10^7	70	8
10^8	78	14

[a] *Populus tremuloides*. This sample was from a board containing a high proportion of tension wood fibers. Tension wood is characterized by an exceptionally high carbohydrate-to-lignin ratio; thus, the high digestibility of this untreated aspen sample in comparison with that shown in Table I.

[b] Roentgen equivalent physical.

of aspen. It does very little to improve digestibility of spruce, however; the maximum digestibility was only 14% at the highest dosage level. Although higher dosage levels would probably improve digestibility further, they would also increase the level of carbohydrate destruction. From earlier work on the use of electron irradiation to enhance wood saccharification (26) it was shown that carbohydrate destruction was about 15% at 10^8 rep. and increased to about 45% at 5×10^8 rep. The product of the latter dosage was almost completely water soluble and was strongly acidic.

Vibratory Ball Milling. The effect of vibratory ball milling on the *in vitro* rumen digestibility of aspen and red oak is shown graphically in Figure 2. *In vitro* digestibilities of both woods increased rapidly with milling time to about 30 min. and then increased more slowly with further milling. Digestibility was highly dependent on time of *in vitro* rumen incubation; at least 5 days of incubation were required for digestibilities to attain 90% or more of their plateau values.

In vitro rumen digestibility of aspen and red oak which had been milled for 240 min. was 80% and 67%, respectively. Results of an enzymatic hydrolysis of the milled products using a cellulase demonstrated that this was not merely a solubilization effect. The 240-min. milled aspen and oak produced 63% and 57%, respectively, of their weight as glucose after enzyme digestion. Sugar production from the unmilled aspen and oak was 10.0% and 0.0%, respectively. Of the total carbohydrates in aspen and red oak, 70-80% was made accessible to cellulase digestion by vibratory ball milling.

In Figure 3 *in vitro* rumen digestibility is plotted as a function of milling time for five hardwood species. The digestibility values are those obtained with 5-day incubation. The first 20-30 min. of milling appear to have the major influence on digestibility. A digestibility plateau is apparently attained beyond which additional milling is of little value.

It is difficult to ascribe definite reasons for the wide variation in response between the woods. Certainly particle size alone is not the governing factor. All wood samples received the same degree of milling, and settling tests in water indicated similar particle size distribution. The controlling factor must be the quantity, chemical nature, and distribution of lignin.

The very selective response of the various species to vibratory ball milling makes this technique of limited value as a general means for upgrading the digestibility of wood residues. Moreover, there is a question whether finely ground wood will function as effectively in the ruminant as it does in *in vitro* assay. With forages, fine grinding has increased the *in vitro* digestibility of cellulose, but it has not produced similar

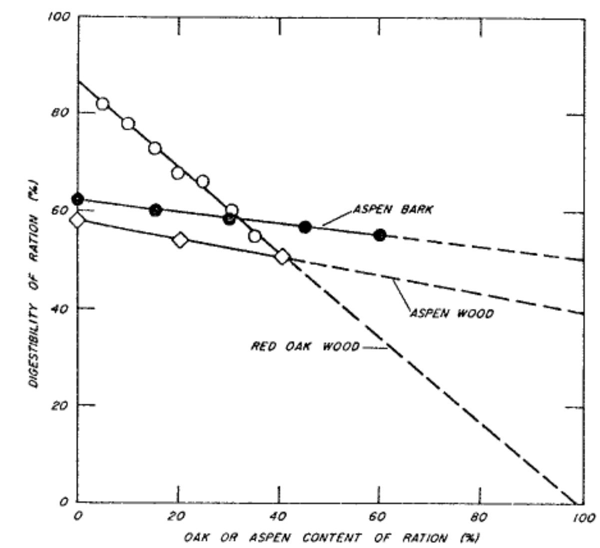

Figure 1. In vivo *digestibility of red oak and aspen wood and aspen bark*

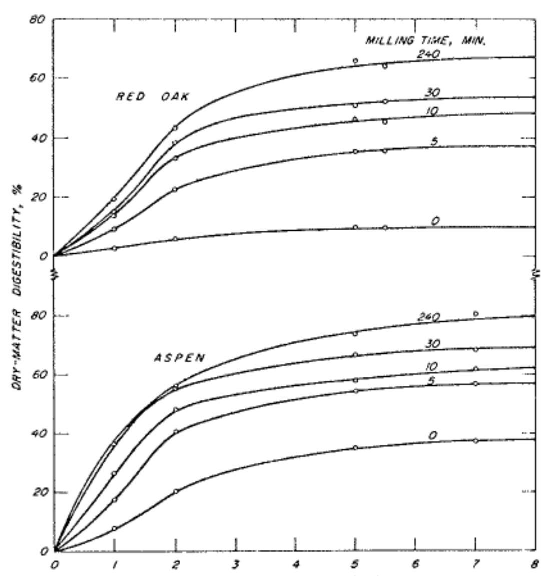

Figure 2. Relation of in vitro *rumen digestibility of red oak and aspen to time of* in vitro *rumen incubation and extent of vibratory ball milling*

responses when fed to ruminants, when digestibility in fact has been decreased. Insufficient residence time in the rumen has been postulated as the cause of the lowered digestibility of finely ground feeds.

Treatment with Anhydrous Liquid Ammonia. As shown in Table III, treatment of aspen sawdust with anhydrous liquid or gaseous ammonia provided a substantial increase in *in vitro* digestibility, raising it to approximately that of hay. There is no significant difference in the digestibilities between the two types of treatment. The effect is rapid; a 1/2-hour treatment with gaseous ammonia at 30° C. yielded the same digestibility value as a 73-hour treatment.

On the basis of X-ray diffraction measurements, total crystalline content was probably not altered sppreciably, but it has been shown that treatment with liquid ammonia causes a phase change from cellulose I to cellulose III (27). Since digestibility of aspen wood was increased to more than 50% with liquid ammonia treatment, support is given the idea that the pertinent action of the treatment is the ammonolysis of cross links of glucuronic acid esters (28).

Hardwoods which have been treated with liquid ammonia and air dried have a markedly increased swelling capacity in water (29). This swelling action provides greater access to the structural carbohydrates by rumen bacteria and their associated enzymes. An additional nutritive benefit is the increased nitrogen content of the ammoniated product through formation of amides and ammonium salts by reaction with the acetyl and uronic acid ester groups of the wood. Kjeldahl analysis of ammoniated aspen showed 9% crude protein compared to 0.5% for untreated wood. Aspen appears to be unique in its digestibility response to ammoniation. The digestibilities of ammonia-treated spruce and red oak were 2% and 7-10%, respectively.

Air-dried aspen sawdust, hammermilled to pass through a screen plate with 1/16-inch-diameter holes, was treated with gaseous anhydrous ammonia and fed to goats in rations containing increasing amounts up to 50% treated aspen. The treatment was done in batches in a 13-cubic-foot rotating digester. The digester, containing the wood, was evacuated to 20 in. Hg for 20 min. and then pressurized to 70 lb. in.$^{-2}$ with anhydrous ammonia for 2 hours. During pressurization, temperature of the wood increased rapidly from 30° C. to a maximum observed temperature of 74° C. and then decreased to 55° C. The decrease was due to heat loss to the metal digester and to the air. It was calculated that the observed temperature rise could have been caused by the heat of reaction of ammonia dissolving in moisture present in the wood. No neutralization of free or adsorbed ammonia on the product was attempted. Ammonia smell from the product was not noticeable after airing the product on the floor for 1 week.

Table III

in vitro Rumen Digestibility of Aspen Sawdust

Exposed to Anhydrous Liquid and Gaseous Ammonia

Treatment[a]		
Chemical	Time	Digestibility
	hr	%
Control	--	33
Liquid NH_3	1	51
Gaseous NH_3	1/2	48
	2-1/2	47
	16	46
	73	46

[a]At 30° C.

Table IV

Effect of Alkali Treatment on the *in vitro* Rumen Digestibility of Various Hardwoods

Species	Yield	Control	Treated[a]
	%	%	%
Trembling aspen	87	33	55
Bigtooth aspen	90	31	49
Black ash	91	17	36
American basswood	89	5	55
White birch	92	8	38
Yellow birch	94	6	19
Eastern cottonwood	93	4	11
American elm	93	8	14
Soft maple	92	20	41
Red oak	94	3	14
White oak	90	4	20

[a] 5-g wood treated for 1 hr with 100 ml of 1% NaOH, washed to neutrality, and dried.

A digestion trial with goats, as was done with aspen bark, indicated an extrapolated *in vivo* dry-matter digestibility of 50%.

Treatment with Aqueous Sodium Hydroxide. The results of *in vitro* rumen digestion show a range of response to the alkali treatment for the various species investigated (Table IV). Aspen and basswood, attaining a digestibility of 55%, are outstanding in their response to alkali pretreatment. The tenfold increase for basswood is especially intriguing. Bigtooth aspen is only slightly less digestible than trembling aspen. Black ash, white birch, and soft maple show an intermediate response with digestibilities ranging between 35% and 40%. The other species have digestibilities of less than 20%. Douglas-fir and Sitka spruce, which are softwoods with a maximum *in vitro* digestibility of 1% and 2%, respectively, did not respond to the alkali treatment. The difference in response appears to be related to the lignin content of the treated hardwoods (Figure 4).

To better define conditions for optimum processing, aspen was treated at room temperature with 0.5% and 1.0% solutions of sodium hydroxide at various liquid-to-solid ratios. Then it was washed to neutrality, dried and assayed. The results in Table V show that from 5-6 g. of NaOH per 100 g. of wood are necessary for a maximum effect on *in vitro* digestibility. This was attained with a 12:1 liquor-to-wood ratio at the 0.5% alkali level or a 6:1 ratio with 1% alkali. It is interesting that the minimum quantity of sodium hydroxide needed for attaining maximum digestibility is roughly equivalent stoichiometrically to the combined acetyl and carboxyl content of the aspen. The main consequence of alkali treatment thus appears to be the breaking (by saponification) of intermolecular ester bonds (28,30). Rupture of these cross links promotes the swelling of wood in water beyond normal water-swollen dimensions; thus it favors increased enzymatic and microbiological penetration into the fine structure of wood. At optimum conditions (6 g. NaOH to 100 g. wood) the yield is about 95%. The 5% loss in weight is caused by saponification and removal of acetyl groups during the water wash.

Treatment with Sulfur Dioxide. It was found that gaseous sulfur dioxide can disrupt the lignin-carbohydrate association *in situ* and yield a product of high digestibility without physical removal of the lignin. Wood in the form of sawdust was reacted for 2 hours (hardwoods) or 3 hours (softwoods) at 120° C. with an initial SO_2 pressure at room temperature of 30 lb. in.$^{-2}$ and a water-to-wood ratio of 3:1 (no free liquid). After blowdown and a brief evacuation to remove adsorbed SO_2, the treated woods were neutralized to about pH 7 with sodium hydroxide and then air dried. Table VI presents analytical data and values for 48-hour cellulase digestion for both the original woods and

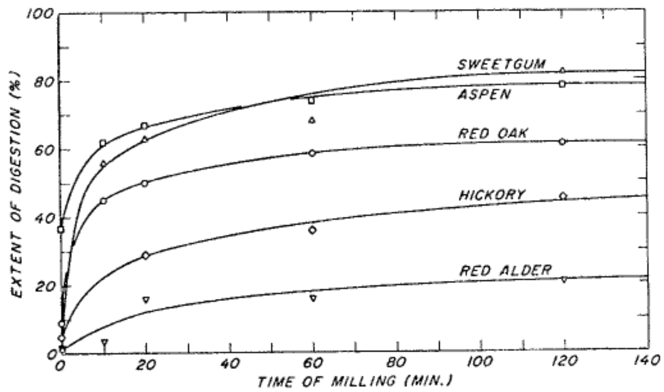

Figure 3. Relationship between in vitro *rumen digestibility and time of vibratory ball milling*

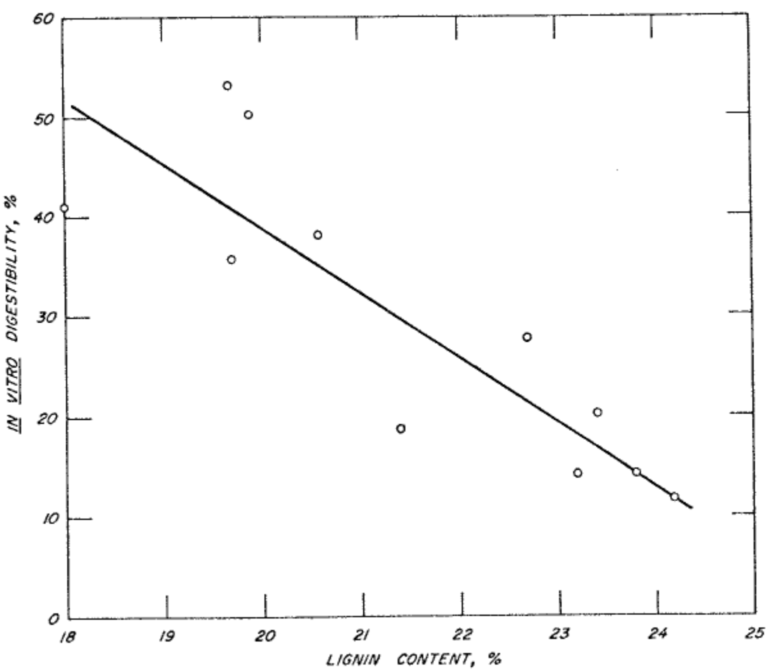

Figure 4. Relationship between lignin content and in vitro *digestibility for NaOH treated hardwoods* (30)

Table V

Effect of Alkali Treatment Variables on the *in vitro* Dry-Matter Digestibility of Aspen

NaOH concen-tration	Ratio of solution to wood	NaOH per 100 g wood	Treating time	Yield	Digestibility
%		gm	hr	%	%
0	0	0	0	100	37
0.5	4:1	2	2	98	47
	8:1	4	2	98	50
	12:1	6	2	95	55
	16:1	8	2	93	53
1.0	2:1	2	1	98	41
	4:1	4	1	96	48
	6:1	6	1	95	51
	8:1	8	1	94	50
	10:1	10	1	93	54
	20:1	20	1	87	50

Table VI

Composition and Cellulase Digestion of Various Woods

Before and After SO_2 Treatment

Species	Lignin		Carbohydrate		Digestibility	
	Before	After	Before	After	Before	After
	- - - - - - - - - - - - % - - - - - - - - - - - -					
Quaking aspen	20	7	70	71	9	63
Yellow birch	23	9	66	67	4	65
Sweetgum	20	5	66	64	2	67
Red oak	26	8	62	60	1	60
Douglas-fir	30	24	65	63	0	46
Ponderosa pine	31	19	59	58	0	50
Alfalfa	17	--	51	--	25	--

the treated products. Data for alfalfa is included for comparison.

Cellulase digestion of the original woods was minimal, from a high of 9% for aspen to essentially 0% for the two softwoods. Even with alfalfa, only half of the available carbohydrate was converted to sugars. Yields of the SO_2-treated products were 106-112% based on starting material, a result of the sulfonation and neutralization reactions. Although all of the lignin was retained in the products, Klason lignin analysis of the five treated hardwoods showed lignin values of only 5-9%. This suggested that the original lignin had been extensively depolymerized during SO_2 treatment and converted to soluble products, a fact subsequently confirmed by extraction with boiling water. Depolymerization was less extensive with the two softwoods, and the higher Klason values are reflected by a decreased digestibility. Enzymatic conversion of the hardwood carbohydrates was essentially quantitative, indicative of a complete disruption of the strong lignin-carbohydrate association in the original woods. The 60-65% digestibility of the treated hardwoods is comparable to the digestibility of a high quality hay. The two softwood products would be equivalent to a low quality hay, but might be upgraded through a better choice of processing conditions.

A 140-kg. batch of SO_2-treated material was prepared from red oak sawdust and fed to goats at levels of 0, 20, 35, and 50% of a pelleted forage ration over an 8-week period to obtain information on palatability, possible toxic side effects, and *in vivo* nutritional value. Average *in vivo* digestibilities for dry matter and carbohydrate as a function of wood content of the rations are plotted in Figure 5. Extrapolation of the curves to 100% SO_2-treated wood yielded values of about 52% for dry matter digestion and 60% for carbohydrate digestion. From the shallow slope of the curves, it appears that a vapor phase treatment with sulfur dioxide effectively converts red oak sawdust into a ruminant feedstuff having the digestible energy equivalence of a medium quality hay. Neutralization of the treated product with ammonia rather than sodium hydroxide would augment its protein equivalence.

Treatment with White-Rot Fungi. White-rot fungi decompose lignin as well as cellulose and hemicellulose in wood. Some remove lignin faster than they do the carbohydrates relative to the original percentage of each. The resulting decayed wood has a lower lignin content than that of the original wood.

Nine white-rot fungi were examined for their ability to remove lignin faster than polysaccharides from aspen and birch wood. During decay most of the fungi decreased the lignin content of the wood; that is, they removed a larger percentage of the lignin than of polysaccharides. Lignin removal was always accompanied by removal of polysaccharides. The decayed woods

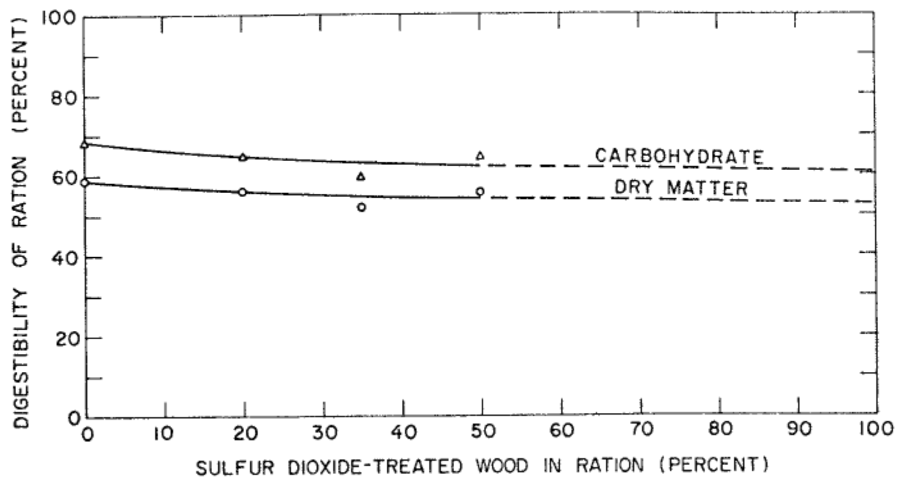

Figure 5. In vivo *dry-matter digestion of rations containing sulfur dioxide-treated red oak*

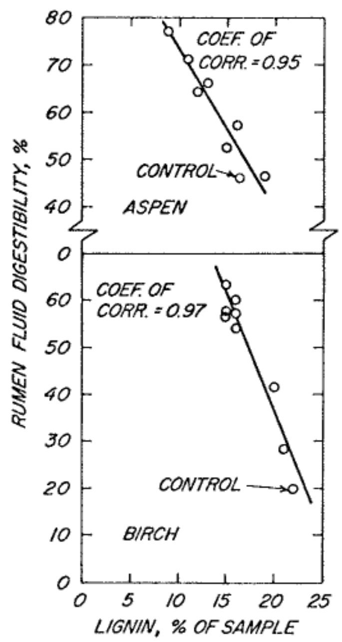

Figure 6. Relationship of in vitro *rumen digestibility to lignin content of white-rotted wood*

have higher in vitro rumen digestibility than the untreated wood and digestibility is inversely related to the lignin content as shown in Figure 6.

Pulp and Papermill Residues and Wood Pulp

Effect of Delignification on Digestibility. Lignin appears to be a major obstacle to microbiological attack of wood. Delignification would then seem to be a straightforward approach to making cellulose available to microbes. To obtain information on the effect of method and degree of lignin removal necessary to make various species digestible, a series of kraft pulps having a range of yields and lignin contents were prepared for in vitro rumen digestibility determination (31).

Four wood species were included: two hardwoods, paper birch and red oak; and two softwoods, red pine and Douglas-fir. Pulping variables were selected to produce pulps with yields from 40-80% and lignin content from 1-32%. Since hemicellulose is removed more rapidly than lignin during the early stages of pulping, some of the high-yield pulps have a higher percentage of lignin than the original wood.

Data showing the relationship between in vitro digestibility and extent of delignification for kraft pulps made from the four species are shown in Figure 7. Extent of delignification is the percent of the lignin removed from the original wood. It is calculated from pulp yield and lignin content of the original wood and the pulp.

Figure 7 shows that an appreciable difference exists in the delignification-digestibility response between hardwoods and softwoods. With the two hardwoods, digestibility increases rapidly with delignification and then approaches a digestibility plateau of about 90% as delignification approaches completion. With the two softwoods, there is a distinct lag phase, especially pronounced with Douglas-fir, during which extensive delignification is accompanied by only minor increases in digestibility. Following this lag phase, digestibility rises rapidly and almost linearly with delignification up to the digestibility maximum.

As interpolated from these four curves, the extent of delignification necessary to obtain a product having an in vitro digestibility of 60%, that of a good quality hay, is shown in Table VII along with data on the lignin content of the original woods and lignin content of the pulp. In common with alkali treatment (Figure 4), digestibility response strongly correlates with lignin content, response being measured in terms of the degree of pulping action needed to achieve a specified level of product utilization. Additional support for this lignin dependency was obtained by Saarinen et al. in an investigation of the in vivo digestibility of a series of birch and spruce pulps prepared by 10 different pulping techniques (32). Recalculation of

Table VII

Degree of Delignification Required to Attain

60% *in vitro* Digestibility

Wood	Required delignification[a]	Lignin in original wood	Lignin in pulp
		%	
Paper birch	25	20	21
Red oak	35	23	20
Red pine	65	27	14
Douglas-fir	73	32	13

[a]Based on original wood.

their data provided the results shown in Figure 8, which also includes curves for red pine and paper birch from Figure 7 for comparison. In spite of the wide variation in delignification techniques employed by the two investigations, the results are quite comparable. This leads to the further conclusion that it is primarily the degree of delignification that governs pulp digestibility, not the method of pulping.

A similar relationship was encountered with respect to the growth of the fungus Aspergillus fumigatus on a variety of commercial pulps prepared under different conditions (33). As determined by the protein content of the fungal mass, reasonable growth on hardwood could be obtained at lignin contents of 14% or less, whereas fungal growth on softwoods was restricted to pulps having less than 3% residual lignin.

Pulp and Papermill Residues. It is estimated that 80 lb. of fiber residues are generated for each ton of wood pulp that is produced and processed into finished products. Thus, more than 1.7 million tons per year of pulp and papermaking fiber residues are produced annually. Most of these residues have undergone at least partial delignification, which increases the accessibility of the wood carbohydrates to the rumen microorganisms and associated enzyme systems. In search for productive outlets for the fibrous residues, in vitro and in vivo estimates of digestibility and chemical analysis for lignin, total carbohydrate, and ash constituents were made on representative samples of commercial residues. On selected residues, feeding trials were conducted to observe ewe and beef steer performance (10).

Data for composition and in vitro dry matter digestibility of various types of commercially obtained pulpmill residues are given in Table VIII. As expected, groundwood fines yielded digestibility values comparable to those observed for sawdust of the same species--0% for the pine and spruce and about 35% for aspen. All of the listed screen rejects and chemical pulp fines had digestibilities of more than 40%, and digestibility of two of the pulp fines was more than 70%. Thus, based on in vitro dry matter digestibility, any of the screen rejects and chemical pulp fines could serve as a useful source of dietary energy for ruminants. The mixed hardwood, kraft bleached chemical pulp fines are essentially pure cellulose.

It can be noted in Table VIII that the Klason lignin and the total carbohydrate contents of the aspen groundwood, aspen sulfite screen rejects, and aspen sulfite parenchyma cell fines are almost identical, whereas the in vitro dry matter digestibility ranges from 37-73%. The digestibility of fines of aspen parenchyma cells, for example, is higher than would be predicted on the basis of lignin content because the parenchyma cells contain substances that analyze as lignin. Microscopic examination

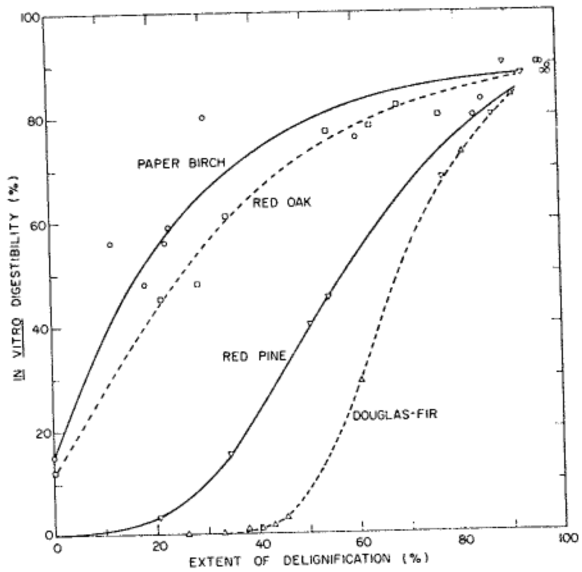

Figure 7. Relationship between in vitro *digestibility and extent of delignification for kraft pulps made from four wood species*

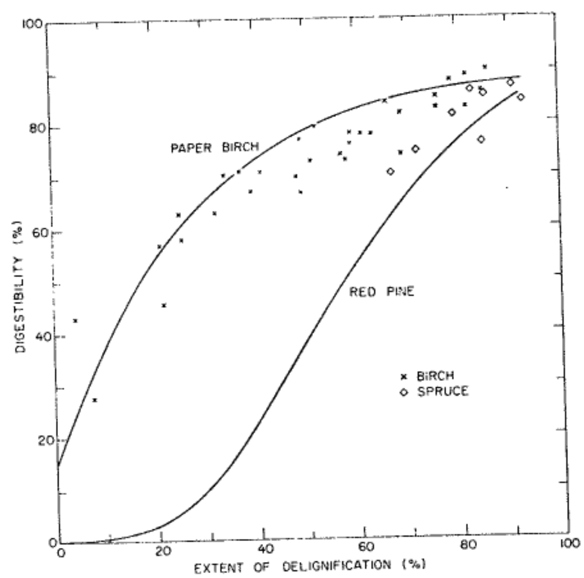

Figure 8. Relationship between digestibility and extent of delignification for wood pulps. (Data points from Saarinen, et al. *(32). Curves from Figure 7.)*

Table VIII

Composition and *in vitro* Rumen Digestibility of Pulpmill Residues

Type of residue	Lignin	Carbo-hydrate	Ash	Digesti-bility
		%		
Groundwood fines				
Aspen	21	73	1	37
Southern pine	31	59	1	0
Spruce	31	60	1	0
Screen rejects				
Aspen sulfite	19	77	2	66
Mixed hardwood, sulfite	24	65	14	54
Mixed hardwood, kraft	25	74	9	44
Chemical pulp fines				
Mixed hardwood, kraft (bleached)	<1	109	1	95
Aspen sulfite (parenchyma cells)	20	73	2	73
Southern pine, kraft (unbleached)	28	68	4	46

Table IX

Composition and *in vitro* Rumen Digestibility of Combined Pulp and Paper Mill Sludges

Type of residue	Lignin	Carbo-hydrate	Ash	Digesti-bility
	- - - - - - - - % - - - - - - - - -			
Groundwood mill				
Mixed species + mixed chemical pulps	50	41	38	24
Southern pine + mixed hardwood kraft	24	60	15	19
Semichemical pulpmill				
Aspen	20	71	2	57
Aspen + mixed hardwoods	55	29	13	6
Chemical pulpmill				
Deinked waste paper, tissue	23	71	22	72
Milk carton stock	28	67	25	65
Mixed chemical pulps, tissue	17	76	13	60
Aspen and spruce sulfite	45	46	45	35

of these fines showed the presence of large quantities of dark resin-like globules. Successive extraction of these fines with ethanol and ethanol-benzene (1/2; v/v) removed more than 15% of the sample. Klason lignin content after extraction was 8.4%.

The digestibilities of the southern pine unbleached kraft pulp fines are also higher than would be predicted on the basis of lignin content. Southern pine wood and the unbleached pulp also contain substances that could analyze as lignin.

Table IX shows the composition and the in vitro dry matter digestibility of various combined pulpmill and papermill primary clarifier or lagoon sludges. Because the groundwood mill sludges are mostly groundwood fiber, the digestibility is expected to be low although the total carbohydrate content is high. The digestibility of this type of sludge will increase as the amount of chemical pulp fiber increases in the sludge. One of the semichemical pulpmill sludges was high in digestibility and total carbohydrate and low in ash, but the other was low in digestibility and total carbohydrate. This indicates the amount of variation that can be expected between mills that use the same pulping process. The digestibility of the other residues ranged from 35-72% with ash contents ranging from 13-45%.

The Klason lignin results also include acid-insoluble paper additives (ash) as lignin. Errors in the lignin analysis are evident in the data listed in Table IX for the combined pulpmill and papermill residues that have high ash content.

Composition of the ash from five pulp residues are shown in Table X, with data for aspen wood and alfalfa hay included for comparison. Except for sulfur, the residues generally exhibit lower levels of the elements P, K, Ca, Mg, and Na than does alfalfa. The Ca level in one residue is higher than that of alfalfa; the Na level is higher in two residues. Certain residues have appreciable amounts of Al and Fe. In some cases, water treatment sludges may enter the clarifiers along with the fiber residue. This would increase the levels of Al and Fe. Residue 7 is high in Zn and Mn, and residues 3, 5, and 7 are high in Cu.

A number of sludges have digestibility values comparable to hay. Their suitability for animal feed, however, will depend on the amount of ash and the chemical nature of the individual ash constituents. For example, moderate levels of clay-type filler could be tolerated, but the presence of more than trace amounts of certain heavy metals would rule out use as a feedstuff. Thus each pulp and papermaking residue should be chemically characterized before it can be recommended as a feedstuff.

Four typical residues--screen rejects from the sulfite pulping of aspen, unbleached parenchyma cell fines from an aspen sulfite tissue mill, unbleached fines from a southern pine kraft mill, and bleached fines from a mixed hardwood southern kraft mill--were blended with other ration ingredients, pelleted and fed to goats, sheep, and steers (10). Results from the

Table X

Composition of Ash From Selected Residues, Aspen Wood, and Alfalfa

Ash constituent	Type of residue[a] 1	2	3	4	5	6	7
				%[b]			
P	0.003	0.23	0.04	<0.01	0.02	<0.01	0.23
K	.06	2.1	.30	.05	.10	<.02	.10
Ca	.18	1.3	2.6	.70	.60	.21	.28
Mg	.03	.30	.04	.04	.08	<.01	.08
Na	.003	.15	.03	.10	.02	.43	.20
S	--	.30	1.5	1.1	.37	.28	.62
				ppm[b]			
Al	16	--	520	66	670	97	540
Ba	19	--	91	13	32	21	16
Fe	35	200	2,300	63	340	95	350
Sr	10	--	44	13	11	6	16
B	3	--	16	2	4	4	14
Cu	6	13	74	6	40	8	99

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Table X

Composition of Ash From Selected Residues, Aspen Wood, and Alfalfa--continued

Ash constituent	Type of residue[a]						
	1	2	3	4	5	6	7
	ppm[b]						
Zn	19	20	14	6	37	4	330
Mn	10	32	44	2	7	9	330
Cr	.3	--	7	1	5	5	13
	%						
Total ash[b]	0.60	8.0	17.4	2.1	2.1	1.8	3.4

[a]1, aspen wood; 2, alfalfa hay; 3, mixed hardwood sulfite screen rejects; 4, aspen sulfite screen rejects; 5, aspen sulfite parenchyma cell fines; 6, mixed hardwood sulfite pulp fines; and 7, southern pine unbleached kraft pulp fines.

[b]Based on moisture-free sample.

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digestibility trials indicate that the *in vivo* dry matter digestibilities are 58, 52, 47, and 78%, respectively. This indicates substantial utilization of the carbohydrate constituents.

The rumen contents of steers fed unbleached southern pine kraft mill fines and steers fed a control ration containing no pulp fines were analyzed for pH, ammonia, volatile fatty acids, and microbial population. No significant differences could be observed between the rumen contents of steers on the control ration and those on the experimental rations.

Steers averaging 226 kg., fed a ration containing 50% unbleached southern pine kraft mill fines, gained 0.5 kg. per day during a 58-day growth trial. During another growth trial, steers averaging 221 kg. were fed a ration containing 75% parenchyma cell fines. These steers gained an average of 0.45 kg. per day during 101 days. These weight gains are not high but they are acceptable wintering growth rates. Feed efficiencies for the two experiments were 11.7 and 16.9 kg. feed per kg. gain.

Rations containing 60% and 75% parenchyma cell fines have been fed to ewes and beef cows with good results. Ewes fed pelleted rations containing 75% fines for one year, and supplemented with additional grain during the last month of pregnancy and during lactation, produced as much wool and weaned as many lambs as did a hay fed control group. Ewes fed a similar ration containing aspen bark in place of pulp fines performed equally as well. Total feed consumption was higher for the groups fed pulp fines and aspen bark reflecting a slightly lower digestibility of these materials compared to hay.

Beef cows fed 2-3 kg. of hay plus a mixture of parenchyma cell fines and grain (83% fines and 17% of grain and mineral supplement) for a period of about 7 months appeared normal in every respect. Palatability of the pulp fines mixture was good.

Summary

The roughage qualities of wood in ruminant rations have been evaluated and compared to other roughages. Wood has been shown to be effective as a roughage replacement. Depending upon the other ration ingredients, concentrations of 5-15% screened sawdust in rations for beef cattle appears practical. For lactating dairy cows, aspen sawdust could be used as a roughage extender or as a partial roughage substitute in high grain rations. Some long hay appears to be necessary in the ration to stabilize feed intake.

The potential of wood and bark, chemically and physically treated wood, and pulp and papermaking residues as energy sources in ruminant rations has been examined by chemical analysis and *in vitro* and *in vivo* methods. *In vitro* rumen and enzyme methods were developed to assay wood-based materials for digestibility.

Of the woods tested, all of the coniferous species are essentially undigested by rumen micro-organisms. Deciduous species, with a few exceptions, are only slightly digested. Aspen is the most highly digestible species tested, giving both an in vitro and in vivo digestibility of about 35%. Aspen bark is about 50% digestible. The resistance to micro-organisms appears to be related to the lignin-carbohydrate complex and the crystallinity of the cellulose.

The coniferous species and most deciduous species were quite resistant to vibratory ball milling, electron irradiation, dilute alkali, and liquid ammonia treatments to increase digestibility. Treatment with gaseous sulfur dioxide appears especially interesting as a way to increase the digestibility of wood. Since no water is added and the product is not washed, yields of over 100% are obtained. The product was accepted by animals during digestion trials.

Delignification of wood by normal wood pulping methods produces materials with high rumen digestibility. It was shown that the digestibility of deciduous species increases rapidly compared to coniferous species as lignin is removed. It was also shown that digestibility depends upon the extent of lignin removal and not upon the method of lignin removal.

Pulp and papermaking residues were analyzed for lignin, carbohydrate, rumen digestibility, ash, and ash constituents. In vitro rumen digestibility of many of the residues ranged from 45-60%; some attained levels as high as 90%. In vivo digestibilities of four typical pulpmill residues ranged between 47 and 78%, and were in reasonable agreement with the in vitro values. Certain residues appear suitable as feed ingredients while others are not suitable because they contain high amounts of ash or contain ash with high concentrations of heavy metal contaminants.

Pulp fines, constituting 50-75% of the ration for steers, ewes, and beef cows were readily consumed. Steer growth rates of approximately 0.5 kg. per day were obtained. Ewes and cows were maintained at an adequate level of nutrition so normal reproduction occurred and growth of nursing offspring was normal. Total feed consumption tended to be higher with the groups fed wood residues, reflecting the slightly lower digestibility of these materials compared to hay.

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