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Agricultural Fibers for Use in Building Components

John A. Youngquist
Andrzej M. Krzysik
Brent W. English
Henry N. Spelter
Poo Chow

Abstract

There is an increasing interest in using agricultural fibers for building components, either to complement or replace wood. This paper provides an overview of how agricultural fibers alone or in combination with wood fibers or other materials can be used for this purpose. Fibrous materials that are most readily available in North America include bagasse, cereal straw, cornstalks, cotton stalks, kenaf, rice husks, and rice straw. These fiber and material options are discussed, and the performance of selected building products are reviewed. For comparison purposes, the commercial standards for particleboard and hardboard are used as a baseline for comparing the performance of panels made from selected agricultural fibers. Results presented in this paper indicate that bagasse, cereal straw, and kenaf appear to have the most promise for panel and component development.

Introduction

Never before has there been so much demand placed on the world's fiber resource system. Economic growth and development worldwide have generated unprecedented needs for converted forest products. Concurrently, the energy needs of developing countries have created ever-increasing demands for fuelwood, which now represents 50 percent of all wood fiber consumption. At the same time, our global fiber production systems have demonstrated the capability to meet these demands on the aggregate. In other words, in spite of tremendous pressures for fiber resources, there is no global fiber shortage or crisis. Yet at the same time, we do have some very serious local/regional fiber shortages and resource management conflicts that will play a critical role in our immediate and long-term future.

Late in the 20th century, people worldwide have become increasingly concerned about the future of forests: their health, wildlife diversity, productivity for wood, environmental roles, and aesthetics. As a result of these concerns, the practices of forestry are changing, resulting in iodized wood fiber supply shortages. The challenge is how to balance all these demands and meet the earth's population and ecological needs simultaneously (38).

In addition, many developing countries around the world do not have adequate forest reserves to cover

The authors are, respectively, Project Leader; Research Specialist; Industrial Specialist; Economist, USDA Forest Serv., Forest Prod. Lab., Madison, Wis.; and Professor, Dept. of Forestry, Univ. of Illinois, Urbana, Ill.

their needs for fuelwood, industrial wood, sawn wood, wood-based building components, etc. However, many of these countries do have relatively large quantities of other lignocellulosic materials available in the form of agricultural residues from annual crops. Many of these lignocellulosics have been used to successfully produce particleboards, fiberboards, inorganic-bonded products, and other building components.

This paper addresses options for using agricultural materials alone or in combination with wood to produce building components. We first review the technology that is available on a regional basis throughout the world. We then discuss agricultural fiber options for North America and provide a brief review of performance properties that can be obtained using those fibers. We close the paper with a discussion of economic considerations affecting the use of agricultural fibers for panels or other building products.

Global perspective

Globally, there are many fiber options. A literature search was conducted at the USDA Forest Service, Forest Products Laboratory, to survey the use of agricultural fibers worldwide (69). A total of 1,039 citations were selected from the vast number available. From these citations, we learned that almost every conceivable type of natural fibrous material has been considered for some type of building material, and many of them are being used worldwide today.

Building components made from agricultural materials fail into the same product categories as other wood-based composition products. Low-density insulation boards, medium-density fiberboards, hardboards, particleboard, and other building system components, such as walls and roofs, are being produced. Binders may be synthetic thermosetting resins, modified naturally occurring resins iike tannin or lignin, starches, thermoplastics, inorganic, or no binder at all. There seems to be little restriction to what has been tried and what may work. The following are highlights selected from the literature search. These highlights are categorized by geographical area, which may be a region or a country.

Africa (Botswana, Nigeria, Sudan)

Port Harcourt, Nigeria (41), was the site of a study to determine if particleboard could be made from agricultural wastes. In the study, naturally occurring tannins from mangrove and red onion skins were used to modify and reduce the costs of synthetic resins. Particleboard with high strength were reportedly made with combinations of bagasse (sugar cane residue), mangrove bark, wood shavings, and corncobs. In Sudan (17), a study to make composition boards from guar and sorghum stalks was undertaken. In Botswana, the Ministry of Agriculture is looking for alternative uses for sorghum (30).

The Americas (Cuba, Mexico, Peru, United States, Venezuela)

The literature search showed that bagasse, the residue fiber from sugar cane processing, is the agricultural fiber of choice in much of theAmericas. The first bagasse composition panel plant was built by Celotex, Louisiana, in 1920. Since then, more than 20 bagasse particleboard plants have been built throughout the world (4). In Venezuela, Tablopan de Venezuela started producing a line of bagasse fiberboards in 1958 (51). Production boards included those of low, medium, and high density. As a result of increased prosperity in Venezuela and a decrease in wood fiber availability, the company purchased a second line in 1975. Sidney (50) describes an insulation board and hardboard plant in Navolato, Mexico. In 1987 (64), bagasse particieboards from the three main factories in Cuba were tested. The board quality was reported to be high, with 21 of 24 samples passing Cuban Standard NC4318:86, which generally agrees with international standards.

Bagasse is not the only agricultural fiber being utilized in the Americas. In Peru, prefabricated panelized construction has been developed using bamboo and wood (34). In this type of construction, prefabricated panels of bamboo and wood are produced using low technology methods. The finished structures are plastered with cement mortar and are said to be earthquake resistant. Wheat and ryegrass straw have been used for the production of panels in the northwest region of the United States (37), and there have been experiments with sunflower stalks and hulls in Minnesota (19,20). Straw bale buildings, which are becoming popular in parts of the United States, usually include concrete foundations, wood framing for door and window openings, conventional roofing, a stucco exterior, and plastered interior walls.

Asia (China, Japan, Taiwan, Thailand)

Although bamboo use is limited in the Western Hemisphere, is use in Asia is widespread. A special building center was established in Kyoto, Japan, after World War II for the development of building materials using bamboo (28). The building center was formed through the cooperation of wholesalers, bamboo producers, and manufacturers.

Bamboo has been processed into a variety of composition panels. A study in Taiwan (7) determined the feasibility of producing oriented and random three-layer boards made from bamboo and wood waste. A similar study (56) showed that Moso bamboo residue and shavings of red cypress exceeded the national Chinese standard. A stressed-skin panel-type product has been produced using ply-bamboo in the faces and polyurethane or polystyrene foam in the core (66).

Other materials are also used in Asia. Bagasse particleboard is made in China (29), soybean stalks have been investigated as well (48). Hardboards have been produced from Thai hardwoods and coconut fiber that meet or exceed Japanese standards (33).

Europe (Bulgaria, Czechoslovakia, Sweden, Germany)

Wood fiber shortages and increased lumber prices make bagasse particleboard an attractive supplement to wood fiber in Sweden. In Sweden, as well as other countries, there is a growing interest in compact, versatile particleboard plants that can handle wood, wood waste, and agricultural materials (10). Sweden is not the only country in Europe that has looked into composition panel production utilizing bagasse. In the former Republic of Czechoslovakia, researchers addressed various production parameters involved with bagasse particleboard production (36). This study addressed depithing and year-round storage

Europeans also feel that there are opportunities for building materials that contain a certain amount of straw. Researchers in Germany produced a variety of wood-straw and straw composition panels (25). In this work boards made from straw at the same resin content and density as those made from wood generally had better properties. In another German study, a series of three-layer boards using straw and softwood particles had slightly different results (55). In this study, straw boards did not perform as well as wood, but all the straw boards met, or nearly met, European standards for particleboard.

Interest by the Europeans in agricultural fibers is not limited to bagasse and straw. A Bulgarian study (57) examined a multitude of agricultural waste fibers. In the study, fiberboards were produced by mixing varying amounts of beech fibers with hemp, tobacco vines, cotton, raspberry, maize, or sunflower stalks. All the wastes were suitable for board production, but the results were obtained with using hemp and tobacco. Bamboo has also been examined in Germany (24). Special winter-hardy varieties have been studied to use in building materials.

India

Binderless particleboard from bagasse have been produced in India (49). The boards were produced by cooking the bagasse in a 1 to 2 percent alkali bath, then tempering the pressed boards with oil. When compared with other agricultural residue panel products in India, bagasse made a good insulation board (52).

Inorganic boards appear to be growing in popularity in India. Researchers and industry have teamed up to develop a variety of building materials using industrial and agricultural wastes that incorporate cement and cementitious materials as binders (40). The resulting combinations are used to produce composition boards, roof sheathing, flooring tiles, and weatherproof coatings.

The Middle East (Egypt, Iraq, Saudi Arabia)

Rice straw is the main lignocellulosic material in Egypt and is used to produce fiberboard. Most rice straw is inferior in quality to that made of wood fiber as a result of the high percentages of nonfibrous materials included in the strew. When care is taken to fiberize the rice straw, board properties increase significantly (12). Other lignocellulosic materials available in the Middle East include cotton stalks, bagasse, and kenaf. One study (15) showed that hardboads prepared from these materials were generally better than those of commercial rice strew composition panels.

In Iraq, particleboards were made with varying mixtures of reed or cattail mixed with wood. Strength properties were significantly increased by the addition of the reed, but water-resistance properties decreased. At 50 percent reed levels, most properties of the panel met or exceeded specifications (l). In Saudi Arabia, bagasse is considered an attractive source of fiber in composites for building materials (62).

Philippines

The Forest Products Research and Development Institute in Laguna, Philippines, has an active research program that examines the utilization of agricultural fibers in the production of composition panels. Much of the research at the institute has focused on coconut coir (or husks) and banana stalks. In one study, coconut coir and pineapple fiber were blended with wood wastes for the production of particleboard (43). In another study of underutilized agricultural species (44), banana stalks were blended with wood chips to make particleboard. Finding uses for banana stalk is warranted, because each banana tree plant produces only one banana bunch and the stalks are generally burned.

USSR

In the former USSR, building materials with high compressive and bending strength have been made using wastes from flax or cotton fabrics and phenol-formaldehyde resin (27). Rice straw boards with excellent properties have also been produced (31). The rice straw was treated with steam and ammonia to increase the natural thermosetting properties of straw. When pressed to high density, the boards had excellent bending strength and minimum water absorption.

Alternative fiber options for North America

Today in the United States, wood is a major source of material for building components, but as we have shown, other sources of fiber are available. These alternative fiber options have the potential to alleviate regional wood fiber shortages, which have been partially created because of renewed concerns about how forests should be used.

For the purpose of this paper, the discussion of alternative agricultural fibers is limited to those that seem most appropriate and available in North America. These materials are bagasse, cereal straw, cornstalks, cotton stalks, kenaf, rice husks, rice straw, sunflower hulls, and sunflower stalks. Technically speaking, any of these agricultural fibers can be used to manufacture composition panels. However, it becomes difficult to use certain kinds of fibers when restrictions in quality and economy are imposed. The remainder of this section addresses the issues of quality, which involves harvesting, handling, manufacturing, and properties of finished panels. The use of straw bales for light-frame wall construction is also discussed. When considering various fibrous crops for panels, commercial standards are used only as a baseline to comparatively judge their performance.

Bagasse

Bagasse is the residue fiber remaining when sugar cane is pressed to extract the sugar. Some bagasse is burned to supply heat to the sugar refining operation; some is returned to the fields; some finds its way into various panel products. Bagasse is composed of fiber and pith. The fiber is thick walled and relatively long (1 to 4 mm). It is obtained from the rind and fibrovascular bundles dispersed throughout the interior of the stalk (23). For the best quality bagasse fiberboard and particleboard, only the fibrous portion is utilized. As may have been ascertained by our continual reference to bagasse, this is the agricultural residue that may offer the greatest opportunity for composition panel production in North America. In what may be considered a definitive work, Atchison and Lengel (4) told the history and growth of bagasse fiberboard and particleboard at the 19th Washington State Particleboard Symposium. In their paper, the authors described the various success and failure stories of bagasse utilization worldwide.

Bagasse is available anywhere sugar cane is grown. In North America, that constitutes just about everywhere between Canada and Mexico. As such, almost no harvesting problems exist. Large volumes of bagasse are available at any sugar mill. In the United States, the cane harvest usually lasts about 2-1/2 months. During this time, bagasse is readily available. For the remainder of the year, the material must be stored. Special care must be taken during storage to prevent fermentation, because bagasse has a high sugar content. To reduce the sugar content and increase storage life, bagasse is usually depithed before storage. The pith is an excellent fuel source for the sugar refining operation. Generally, if the bagasse is depithed, dried, and densely baled, it can be stored outside. If handled in a careful reamer, bagasse can also be stored wet. In the wet method, large bales of bagasse are specially fabricated and stacked to ensure adequate air flow. Heat from fermenting sugars effectively sterilize the bales. Bagasse can be stored several years using this method (6). Other storage options are available, including some that keep the bagasse wet beyond the fiber saturation point.

As mentioned, only the bagasse fiber is utilized for the production of the highest quality composition panels. As such, various schemes are available to separate the bagasse fiber from the pith. After depithing, the fibers are more accurately described as fiber bundles. These fiber bundles can be used “as is” to make particleboard, or they can be refined to produce fibers for fiberboard. In either product, dry or wet layup is possible. Some properties of bagasse composition panels are shown in Figure 1.

Cereal straw

Cereal straw is probably the second most comon agricultural fiber for reconstituted panel production. For the purpose of this paper, cereal straw is meant to include straw from wheat, rye, barley, oats, and rice. Straw, like bagasse, is an agricultural residue. Unlike bagasse, large quantities are generally not available at one location. Storage is usually accomplished by baling. Straw has a high ash content (Table 1) and they tend to fill up fireboxes in boilers and increase the wear rate on cutting tools. Their high silica content tends to make them naturally fire resistant (42).

Plants have existed in several countries to make thick (5 to 15 cm) straw panels with kraft paper faces (59). The panels are made by heating the straw to about 200°C, at which point springback (i.e., nonrecoverable thickness swelling) properties are virtually nothing. The straw is fed through a reciprocating arm extruder and made into a continuous low density (0.25 specific gravity) panel. Kraft paper is then glued to the faces and edges of the panels. These panels can be cut for prefabrication into housing and other structures. The low density of these panels makes them fairly resilient, and test data show that housing built using these panels are especially earthquake resistant. In the 1980s, such a plant was setup in California to produce straw panels from wheat and rye straw (18).

Straw can be used to supplement part of the fiber content in particleboard. One of the largest particleboard plants in the United States, located in La Grande, Oregon, substituted straw at a rate of 8 percent and found no major problems except that the sander dust from the faces deposited more ash in the boiler. They stopped using straw in the face and used it only in the core. At a rate of 10 percent or less, the effect on tool wear was not significant (32).

An article in *Environmental Building News* (67) covers straw as a building material in detail and includes several references specific to this building technology. The following text summarizes information from this article.

Unprocessed baled straw is being used to build homes in most states and provinces in North America and is starting to be used in Latin America. European countries, inciuding France, England, Finland, and Russia, are also using this unique construction technology.

There are two primary ways to build with strew bales. In load-bearing straw bale construction, bales are stacked and reinforced to provide structural walls that carry the roof load. With in-fill straw bale construction, a wood, metal, or masonry structural frame supports the roof, and bales are stacked to provide nonstructural insulating walls. With either alternative, the bale walls are plastered or stuccoed on both the interior and exterior. One primary benefit claimed for straw bale building systems is that extremely high insulation values can be obtained. Insulation testing completed to date on the two referenced bale construction methods has produced quite variable results, although there is no doubt that the bales produce extremely good insulation properties. It has also been reported that tightly compacted straw bales are fire resistant, due to dense packing. In addition, high silica content in straw is said to impede fire because as burning begins, a layer of char develops, thus insulating the inner straw. Building codes in the United States have approved straw-bale construction on a case-by-case basis, usually under the "Alternative Materials and Methods" section of the relevant building codes.

In addition to straw bale construction, *Environmental Building News* (67) reports that there are at least 10 companies currently building or planning to build manufacturing plants in North America to produce compressed-straw building panels, with applications ranging from interior partitions to particleboard (Table 2). Figure 2 shows a house built with straw bales, before the stucco is applied.

The time of harvest for the straw is important to board quality (45). The quality of the straw is highest when the grain is at its optimum ripeness for harvest-

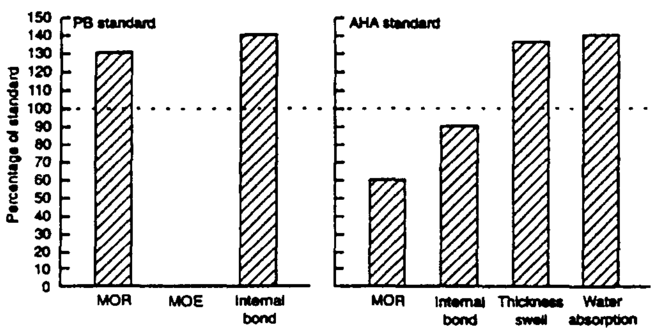

Figure 1.—Some properties of bagasse composition panels. Thickness swell and water absorption values below dotted line are desirable. PB = particleboard; AHA = American Hardboard Assoc. Source: (2,3,46).

Table 1.—Chemical composition of selected lignocellulosic fibers.

Fiber type	Composition[a]			
	Alpha cellulose	Lignin	Ash	Silica
	(%)			
Rice straw[b]	28 to 36	12 to 16	15 to 20	9 to 14
Wheat straw[b]	38 to 46	16 to 21	5 to 9	3 to 7
Oat straw[b]	31 to 37	16 to 19	6 to 8	4 to 7
Bagasse[b]	32 to 44	19 to 24	2 to 5	1 to 4
Kenaf[b]	31 to 39	14 to 19	2 to 5	NA
Cotton stalks[c]	NA	22	5	3
Rice husks[d]	38	22	20	19
Softwoods[b]	40 to 45	26 to 34	<1	--
Hardwoods[b]	38 to 48	23 to 30	<1	--

[a] NA = not available; -- = negligible value.
[b] Source: (53).
[c] Source: (13).
[d] Source: (22).

ing. Underripe straw has not yet yielded its full potential and overripe straw becomes brittle. Ryegrass straw particleboard is commercially produced in the United States in Oregon (37). The product has a density of 0.6, is quite stiff, and has a Class 3 fire rating (42). Properties of straw composition panels are shown in Figure 3.

Cornstalks and corncobs

Based on our literature search, there is currently no commercial utilization of cornstalks or corncobs in composition panel production. A three-layer board having a corncob core and a wood veneer face was produced for a short time in Czechoslovakia after World War II (59). It is recorded that the process was too labor-intensive and was discontinued.

Cornstalks, like many other agricultural fiber sources, consist of a pithy core with an outer layer of long fibers. Currently in the United States, cornstalks are chopped and used for forage, left on the field, or baled for animal bedding. The cobs are occasionally used for fuel. Research has shown that cornstalk and cobs can be made into reasonably good particleboard and fiberboard (8). In the research, cornstalks and cobs were either hammermilled into particles or reduced to fibers in a pressurized refiner. Urea formaldehyde resin was added at the 7 percent level; 1 percent wax was also added. Some panels were laminated with 3.2-mm pine veneers, and three-layer panels were made with stalk faces and cob cores. Selected results of this research are shown in Figure 4.

Cotton stalks

Cotton is cultivated primarily for its fiber; little use is made of the plant stalk. Stalk harvest yields tend to be low and storage can be a problem. The cotton stalk

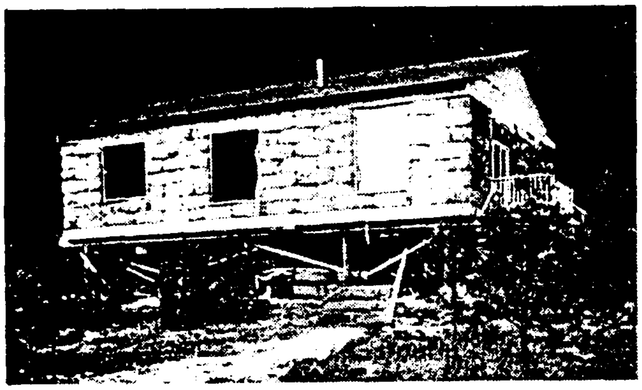

Figure 2.—A house built with straw bales, before the stucco is applied.

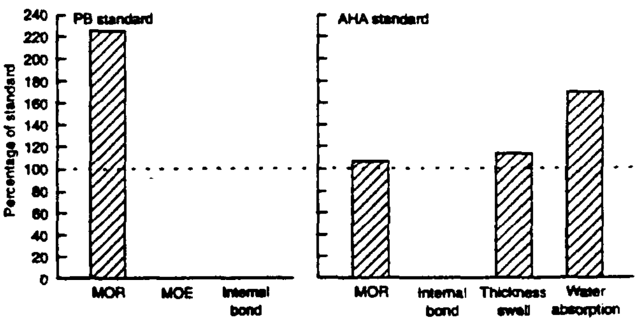

Figure 3.—Some properties of straw composition boards PB = particleboard; AHA = American Hardboard Assoc. Source: (2,3,14).

Table 2.—Some straw panel products.

Company	Manufacturing location	Product description and applications
Stramit Industries, Ltd.	Suffolk, England	Easiwall panel for interior partitions
Stramtech Building Systems	Victoria, Australia	Stramit-type Easiboard ceiling and wall panels
Stramit USA, LLC	Perryton, Tex.	Stramit-type panel for interior partition walls
Alternative Construction Products Corp.	Baker, Mont.	Stramit-type wheat straw panel for interior partition walls
BioFab—AltMatTec	Redding, Calif.	Stramit-type rice straw product; building envelope system
Pyramid International, Inc.	Production mill briefly operational in Texas (1980s)	Stramit-type panels in structural building system
Basic Industry Technology, Inc.	Willamette Valley, Oreg.	Structural building system using rye straw Agriboard panels
Agriboard Industries, L.C.	Fairfield, Iowa	Structural insulated building panels with compressed straw
PrimeBoard, Inc.	Wahpeton, N.D.	Furniture-grade wheat straw particleboard
Isoboard Enterprises, Inc.	Elie, Manitoba, Canada	Furniture-grade straw particleboard
Sea Star Trading Company	Albany, Oreg. (projected restart by mid-1995)	Medium- to high-density fiberboard

Source: (67).

is plagued with parasites, and stored stalks can allow the parasites to winter over for next year's crops. Attempted commercialization of cotton stalk particleboard in Iran was unsuccessful for this reason (5).

If the parasite issue can be addressed, cotton stalks can be an excellent source of fiber. With regards to structure and dimensions, cotton stalk fiber is similar to common species of hardwood fiber (39). As such, debarked cotton stalks can be used to make high grades of paper. The stalk is about 33 percent bark and quite fibrous. Newsprint quality paper can be made from whole cotton stalk. Some properties of composition panels made from undebarked cotton stalk are shown in Figure 5.

Kenaf

Kenaf is a plant that is similar to jute or hemp. It has a pithy stem surrounded by fibers. The fibers represent 20 to 25 percent of the dry weight of the plant (35). Kenaf grows well in the southern United States. Growth in the northern United States fluctuates with variations in the growing season. Mature kenaf plants can be 5 m tall.

Kenaf is currently generating a great deal of interest from government and industry. The U.S. Department of Agriculture is promoting kenaf and other nonfood, nonfeed agricultural crops, because they are not subject to subsidies (60).

Historically, kenaf fibers first found use as cordage. Industry is exploring the use of kenaf in papermaking and nonwoven textiles. Kenaf fiber can be used to make letterhead quality paper. Whole kenaf stalks can be used to make newsprint grade paper. With the pith removed, kenaf and other fibers have been blended together to make nonwoven textile mats. As a nonwoven textile mat, kenaf can be used for erosion control, seedling mulches, oil spill absorbents, or other uses. When a resin is added to the kenaf mats, they can be pressed into flat panels or molded into shapes like interior car door substrates.

As an indication of the interest in kenaf, a recent USDA bibliography was devoted solely to kenaf and had 241 scientific citations (61). There is also an association devoted to the study and promotion of kenaf called the International Kenaf Association (54). Research on the use of kenaf for composition panels has been somewhat limited, although encouraging. In our literature search, there were two references containing data on composition panels made from kenaf. Unpublished research at the Forest Products Laboratory has shown that kenaf can be used to make fiberboard equal or nearly equal to American National Standard Institute and American Hardboard Association basic hardboard standards. Some selected properties for kenaf composition panels are shown in Figure 6.

Rice husks

Rice husks are an agricultural residue and, like bagasse, are available in fairly large quantities in one area. Rice usually comes to the mill with about 8 percent moisture content (65). Rice husks are quite fibrous by nature and require little energy input to prepare the husks for board manufacture. To make high quality boards, the inner and outer husks are separated and the husks are broken at their "spine" Resin is applied; then the rice husk particles are airlaid like any other lignocellulosic material.

Rice husks or their ash have found their way into cement block and other cement products. The addition of the hulls increases thermal and acoustic prop erties (22). Properties of selected rice husk composition panels are presented in Figure 7.

Sunflower stalks and hulls

The University of Minnesota was the site of several studies to examine the properties of particleboards

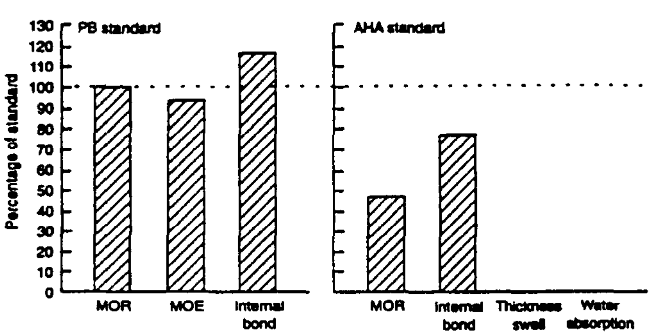

Figure 4.—Selected results of cornstalk composition board research. PB = particleboard; AHA = American Hardboard Assoc. Source: (3,4,8).

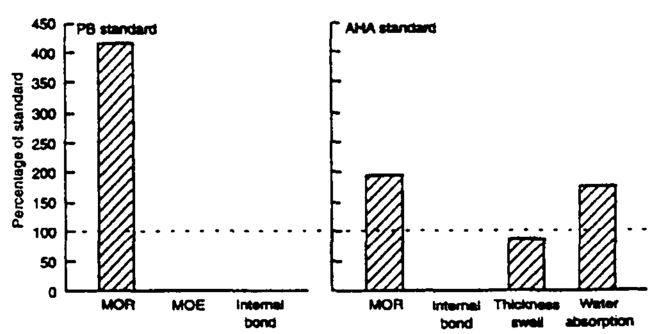

Figure 5.—Some properties of undebarked cotton stalk composition panels. PB = particleboard; AHA = American Hardboard Assoc. Source: (3,4,14).

made with varying amounts of sunflower stalks and hulls (19,20). In the first study, particleboard produced from 50 percent aspen and 50 percent sunflower hulls were made. The next study focused on sunflower stalks, prepared and depithed in different ways, and blended with aspen flakes. The results indicated that most physical and mechanical properties were increased by the addition of the fibrous sunflower stalks.

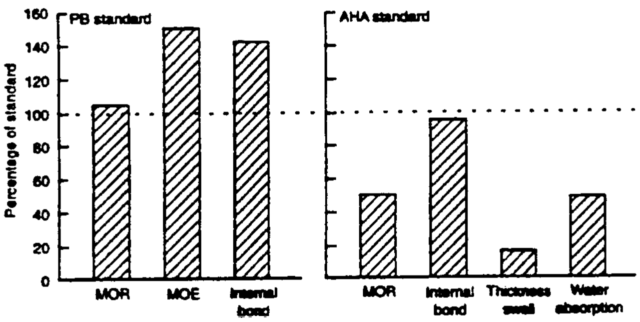

Figure 6.—Some properties of kenaf composition panels. PB = particleboard; AHA = American Hardboard Assoc. Source: (3,4,8).

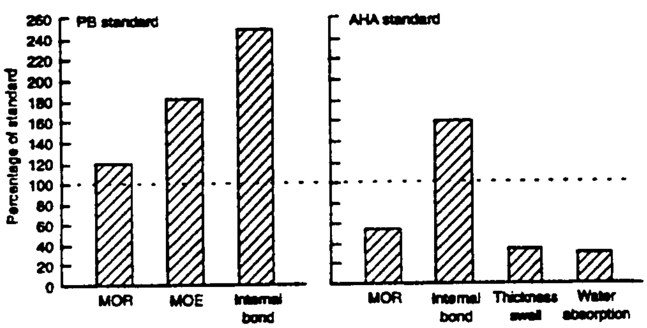

Figure 7.—Some properties of rice husk composition panels. PB = particleboard; AHA = American Hardboard Assoc. Source: (3,4,22).

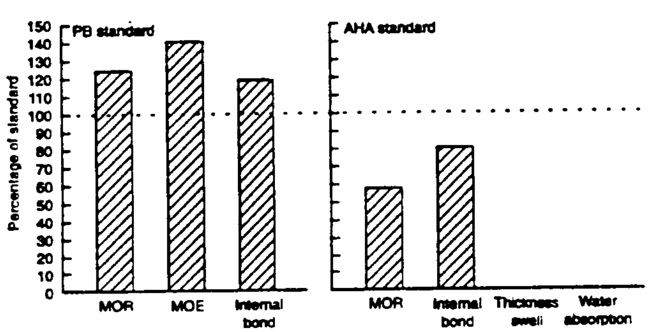

Figure 8.—Some properties of sunflower stalk composition panels. PB = particleboard; AHA = American Hardboard Assoc. Source: (3,4,19).

Our literature search found only one citation for sunflowers outside the United States. Within the United States, two citations were found for hulls and one for stalks. At the time of this writing, we are unaware of any commercial use of sunflower stalks or hulls in composition panels. Properties of composition boards made from sunflower stalks are shown in Figure 8; properties for composition panels made from sunflower hulls are shown in Figure 9.

Fiber availability and economics

Given that agricultural residues and other nonwood fibers can be used to make panels of comparable mechanical properties, the question is: Are these fibers available and economical to use?

Fiber availability

Considerable amounts of agricultural residues are generated each year in the United States (Table 3). If the unlikely assumption was made that 75 wood composition panel mills decided to switch over entirely to agricultural fiber and if it was assumed that, on average, each particular mill required 135×10^3 tons of fiber a year, the total fiber requirement would be

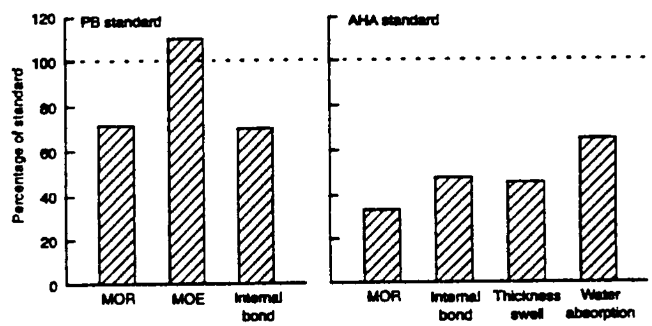

Figure 9.—Properties of sunflower hull composition panels. PB = particleboard; AHA = American Hardboard Assoc. Source: (3,4,8).

Table 3.—Residue estimates of major U.S. crops.

Crop	Harvested		Yield per hectare		Estimated 1990 residue weight
	(ha)	(acre)	(ton/ha)	(ton/acre)	($\times 10^6$ ton)
Corn	26	65	5 to 7	2 to 3	167
Wheat	24	60	2 to 5	1 to 2	106
Sorghum	6	16	5 to 7	2 to 3	23
Oats	6	14	2 to 5	1 to 2	9
Barley	4	11	2 to 5	1 to 2	11
Rice	1	2	2 to 5	1 to 2	2
Total					318

Source: (21).

approximately 10 × 10^6 tons. Therefore, more than 30 times as much agricultural fiber would be available as would be consumed. This calculation of availability does not take into account bagasse or agricultural fibers from nonresidue sources like kenaf. Thus, from the viewpoint of potential availability, the amount of residues generated by U.S. agriculture far exceeds present and foreseeable composition panel fiber requirements.

However, not all the gross potential supply is freely available. For instance, in order to participate in U.S. federal farm programs, all farms must have an approved conservation plan by 1995. In some cases, this entails leaving some portion of the residue mass on the ground as cover for soil protection. It should also be mentioned that these fibers are available on a seasonal basis only. Storage issues for many of the individual fiber types are addressed elsewhere in our paper.

Fiber economics

In North America, composition panels have primarily come from wood residues and secondarily from roundwood obtained from traditionally managed forests. How alternative fiber sources compare in cost with these traditional sources will determine the extent to which they can be considered as a wood fiber substitute. Alternative agricultural fiber comes from two main sources: agricultural crops grown for fiber (e.g., kenaf) and residues of crops grown for other purposes (e.g., wheat, cotton).

Fiber yields

Intensively managed hybrid poplar grown under short rotations can produce yields of fiber ranging from 10 to 15 tons/ha (4 to 6 tons/acre) per year. Conventionally managed aspen stands yield about 2.5 tons/ha (1 ton/acre) per year (11,58). From the viewpoint of maximum yields, kenaf appears to be preeminent. Yields of up to 50 tons/ha (20 ton/acre) on the best sites have been reported (9), although 15 tons/ha (6 tons/acre) is more realistic. When fiber yields of crop residues are examined, the range of harvestable fibers varies from 2 to 7 tons/ha (1 to 3 tons/acre), depending on plant species and local growing conditions (Table 3).

Bulk density

A major difference between wood and nonwood fibers is bulk density. One obstacle to agricultural fiber utilization for relatively low-value commodity products, like composite panels, is low bulk density, which can significantly increase transport costs. A standard cord of wood contains 3.6 m^3 (128 ft^3) of space, of which approximately 2.1 m^3 (76 $ft.^3$) is wood. This yields a gross bulk density (dry basis) of 240 to 320 kg/m^3 (15 to 20 $lb./ft.^3$). The economics of processing and transporting small-diameter timber with such bulk density indicates a practical procurement radius of about 65 km (40 miles) (63).

In contrast, annual fiber sterns of a plant, such as kenaf or straw, cannot be compacted much beyond 135 kg/m^3 (8.4 $lb./ft.^3$), which limits the feasible supply basin to a range of 25 to 35 km (15 to 20 miles) (47). By analogy, we would expect similar ranges to hold for residue fibers as well, if the same high-density baling equipment as assumed in the Sandwell and Associates (47) study were available. This effectively reduces the availability of fiber to a single processing plant to an area of approximately 320,000 ha (800,000 acres). Assuming that 70 percent of this land was devoted to agriculture and that fiber producing plants were planted on a third of the acreage in a given year, the available supply, based on a 5 tons/ha (2 tons/acre) yield, is about 375,000 tons. This provides a coverage ratio of 2.75 for the needs of a typical mill, based on previously given assumptions.

Alternative uses

Not all the fiber produced in U.S. agriculture is a valueless byproduct. For example uses and markets for baled straw exist where animal bedding needs are high, such as in states where dairy farming is strong. In Wisconsin and Pennsylvania, two states where the availability of straw relative to the number of cows in

Table 4.—Various cereal straw prices.

U.S. state	Cereal straw availability per year	Number of milk cows	Ratio (straw/cow)	Price range
	(×10^6 ton)	(×10^6)		(US$/ton)
Kansas	24.5	0.10	250	--
North Dakota	23.3	0.09	250	25 to 35
Washington, Oregon	15.2	0.31	50	--
Montana	12.9	0.23	55	--
Texas	11.6	0.38	30	--
Oklahoma	11.4	0.10	110	--
Minnesota	10.2	0.78	15	--
Illinois, Indiana	10.2	0.38	25	--
California	8.9	1.10	8	--
Nebraska	7.6	0.11	70	--
Wisconsin	2.2	0.76	1.2	60 to 90
Pennsylvania	1.6	0.77	2.0	50 to 95

Source: (16,21,26).

dairy herds is small, baled straw delivered to central auction sites is priced from $50 to $90 per dry ton (Table 4). In North Dakota, straw is generally left on the ground. The small volumes of straw that are baled and marketed fetch a price of only $25 to $35 per dry ton. In other areas, although straw is not priced, it plays a valuable role in agriculture as a mulch to retard runoff and soil erosion. The use of straw for these conservation purposes is mandated by U.S. federal farm programs. Nevertheless, much of the straw produced has little economic value and would be available for other off-site uses at a low cost.

Cornstalk residue has lower absorbency than straw and is not as well suited for bedding purposes. It has been estimated that cornstalks could be obtained for as little *as* $5 per ton, unbaled (on the stump). Factoring in harvesting and transport costs, such material should be obtainable for $25 per ton.

Overall price comparisons

For this analysis, current costs of pulpwood as a frame of reference were used. Pulpwood in the United States is usually marketed in terms of cords, thus a conversion to weights, based on species density, was made to facilitate comparison with agricultural residues. The results of the comparison are in Table 5.

Recent pine, mixed hardwood, and aspen pulp wood delivered prices range from $43 to $52 per cord (3.6 m^3). When converted to a weight basis, prices range from $40 to $47 per ton. Intensively cultivated hybrid poplar plantations prices are estimated at $60 per ton, exceeding pine and hardwoods prices. Hybrid poplar estimates assume a 15 tons/ha (6 tons/acre) yield and two harvest rotations following initial harvest, involving coppice regeneration (which eliminates replanting costs).

Among the agricultural fibers, kenaf is generally the highest in estimated price, because all the costs of cultivation and harvest have to be born by the fiber component of the output. The kenaf calculations are based on 15 tons/ha (6 tons/acre) yields, and the price falls between those of hybrid poplar and pine or hardwood pulpwood. Straw and corn are generally lower in cost, because the grain portion of the output bears the expenses. An exception to this is where the fiber has value for other uses, such as animal bedding. In those cases, straw prices can be almost twice as high as pulpwood and not currently within economic reach of particleboard producers.

Concluding remarks

In this paper, we explored the uses of alternative agricultural fibers from a global perspective. We discussed agricultural fibers that have been or could be used in North America. We discussed those issues that a producer of wood-based composition panels would find most interesting, and we provided information on building systems that utilize straw in baled and compressed panel form. From this discussion, we conclude the following:

Table 5.—Relative prices of wood and agricultural fibers.

Pulpwood/fiber	Prices[a]					
	Stumpage[b]		Harvested and delivered		Total	
	(US$/ton)	(US$/cord)	(US$/ton)	(US$/cord)	(US$/ton)	(US$/cord)
Pulpwood						
Southern pine[c]	16	20	25	32	41	52
Southern hardwood[c]	8	9	31	34	40	43
Lake States[d]						
Aspen	13	12	34	33	47	45
Hybrid poplar	40	--	20	--	60	--
Kenaf	36	--	19	--	55	--
Agricultural fiber[e]						
Cereal straw	5 to 70	--	20	--	25 to 90	--
Cornstalks	5	--	20	--	25	--

[a] Conversions based on 2 m^3 (77 $ft.^3$) per cord.

[b] Stumpage is growing cost plus return to land and farmer; for kenaf, straw, and corn, cost of harvest is included in stumpage.

[c] Source: (68).

[d] Aspen prices from Wisconsin and Minnesota state forestry officials; hybrid poplar based on (58); kenaf based on (47).

[e] Based on partial survey of state agricultural extension economists.

- There is no global wood fiber shortage. However, there are a number of examples of localized supply shortages throughout the world.
- There is a large body of literature that reports on the satisfactory use of agricultural fibers in composition panels and building systems.
- There are more than enough agricultural fiber residues to support composition panel manufacturing needs within North America. However, the fibers may not be in the right place at the right time.
- In general terms, composition panels made from agricultural fibers are somewhat poorer in quality than those made of wood, but blending in small amounts (10 to 20%) of agricultural fibers may have no significant impact.
- Bagasse, cereal straw, and kenaf appear to hold the most promise for continued development.

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