

Wheat straw as an alternative pulp fiber

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ABSTRACT: The desire to market sustainable packaging materials has led to an interest in the use of various fiber types as a raw material. It has been suggested that the use of annual crops for partial replacement of wood fiber would result in more sustainable products. Several life cycle analyses (LCA) have been performed to evaluate these claims. These LCAs provided conflicting and contradictory results because of the local conditions and the specific pulping processes investigated. Selected LCAs are reviewed and the underlying reasons for these conflicting results are analyzed.

Of all the agriculturally sourced annual fibers available, other than wood, only straw pulp is currently available in commercial quantities. A careful review of the available data suggests that neither an annual crop nor wood are more sustainable in general. Countries that allow burning of straw after harvest present a unique situation. Each situation needs specific and direct comparisons that are not generally available. The use of straw fiber in place of wood fiber does not appear to present any advantages to either the environmental impact of production or to the final product quality. The impact of substitution of straw fiber for hardwood pulp in bleached board applications and for high yield pine in linerboard applications has been examined in handsheet studies. In general, the partial substitution of straw pulp for wood pulp does not improve the handsheet physical properties. These studies suggest that straw pulp should be used in low fiber strength requirement applications, such as tissue and molded fiber products. Commercial progress of straw pulping by Kimberly-Clark and Essity in low fiber strength requirement applications is a sign that the nonwood fiber opportunity has growth potential.

Application: As a routine part of sustainability and new product efforts, fiber from wheat straw was evaluated as a potential partial replacement for hardwood kraft fiber. Sufficient technical gaps in the areas of availability, pulping and bleaching, transportation and storage, and physical strength properties remain, making the use of this material suitable only for specialty niche markets at this time. No clear-cut sustainability advantage of using an annual fiber was determined for this product.

As part of the sustainability efforts in the paper industry, periodic reviews of alternative fiber applications are performed. These fibers are evaluated for their potential incorporation into the existing fiber mix and for their potential for opening new or improved market segments. Over the last few years, there has been a significant increase in the potential use of annual crop-based fiber as a component of packaging, based upon the allure of a more sustainable packaging material. Customers have made inquiries about wheat straw, bamboo, Arundo, flax, bagasse, and hemp fibers. Of these fibers, only straw is currently available in commercially viable quantities. Hemp, Arundo and bamboo would need to be cultivated near mill sites in order to be viable as a wood fiber alternative [1]. The commercial availability of these fibers will depend on the value proposition presented to the farming community. All these fibers still exhibit several commercial and physical property deficiencies that need to be overcome before they will be accepted into the current fiber mix for packaging solutions as more than a mere niche product.

Some of the perceived improvements in sustainability have been bolstered by a proliferation of claims and certifications

associated with the use of annual crop-based fibers as a replacement for wood pulp [2-6]. Unfortunately, the environmental impacts of sourcing fiber from wood or nonwood resources are not directly comparable because of the local environments, the processes employed, and the end use of the products. Nonwood fiber from wheat straw is attractive as a partial hardwood substitute where pulp mills have limited hardwood supply [7]. Many of the challenges with use of straw pulp arise from the need to store a whole year's supply from a single harvest season without substantial yield losses due to decay or fires [8]. Transportation of material to the mill has been claimed to have both positive and negative environmental impact [8]. Environmental impact from both wood and nonwood sources are mostly a result of the pulping process, followed by the pollution generated by resources used to collect the fiber. Pulping chemicals are recovered and re-used with high efficiency with wood pulp, and energy is generated for running the mill in this process, but recovery processes are usually not available to nonwood mills. Some straw pulping processes lose pulping chemicals as part of a byproduct plant nutrient (sometimes called low grade fertilizer). Other processes use low efficiency recovery processes such as a Copeland process or a combined heat and energy process.

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Often, the difference between the high efficiency kraft pulping and recovery process and the lower efficiency straw process is ignored in life cycle analysis (LCA) assessments.

The intensive use of fertilizer for nonwood fiber cultivation has often been used as a negative comparison with wood fiber. A counter argument has been that, since straw is a crop residue, fertilizer was used for the production of food and not for production of straw. An advantage of using crop residues, particularly wheat straw, is a reduction in the amount that would be burned at the end of the season. The use of straw pulping chemicals to produce black liquor to be used as a fertilizer for crops is an added benefit for farming and a necessity for the pulp mill. The installation of mini-mills to serve local communities provides a source of additional income for farmers, new employment, and relief from pollution generated by burning excess straw in the field. Burning of straw is being banned in more and more locations, thus removing this advantage of straw fiber from an LCA accounting.

Life cycle analyses of straw pulp

There are a plethora of life cycle analyses (LCAs) for straw pulp available in the literature [9]. The LCAs are highly dependent upon the choice of fiber source for comparison and where exactly the boundary conditions of the analysis are drawn. As a result, it is easy to produce an LCA that is heavily biased towards annual crop fibers such as straw [3]. Many of the LCAs performed for multiple nonwood fibers have indicated that straw is the most sustainable of the nonwood fibers [7]. Often, the comparison is strongly biased by comparing local, unbleached high yield straw pulp as a partial replacement for fully bleached Canadian boreal softwood being transported to Alabama, rather than locally sourced plantation wood [3]. Other analyses devalue the fertilizer demand component of straw production by stating the fertilizer will be required for wheat regardless of the straw utilization [8]. Several of the LCAs do not account for the highly efficient regeneration and reuse of pulping chemicals and energy associated with wood pulping, thus artificially increasing the cost and impact of wood pulping. Since kraft pulping results in 96% (older) to 98.5% (newer) recovery of pulping chemicals and a significant generation of power from biomass sources (black liquor), the pulping and recovery cycle must be included in any believable assessment.

LCA analyses can also be skewed against straw pulping. Some LCA studies have unfairly employed data from older pulping methods, with examples primarily from China, for example, using caustic to pulp straw to a 30% yield in order to produce a kraft pulp substitute but one that drains poorly and results in extensive organic carryover into the bleach plant and to the environment. China has been consistently shutting down these types of straw and bagasse pulp mills due to inefficiency and high levels of pollution [10,11]. Life cycle analyses comparing wood and nonwood pulp production largely rely on data from outdated nonwood mills in Asia that do not have the benefit of improvements currently being

made in the pulping processes, as reviewed below. An example of this type of analysis is a study done for the World Business Council for Sustainable Development by the International Institute for Environment and Development, which concluded that the use of nonwood fibers results in more pollution and is less environmentally friendly than the use of almost all species of wood fiber [12].

NGOs and political action groups

As a result of the multiple LCAs with a variety of local conditions, several different groups have attached significant sustainability claims to the use of annual crop-based fibers. Many of the arguments by non-governmental organizations (NGOs) and political action groups in favor of the use of nonwood fiber focus on unsustainable harvesting of old growth boreal forests, primarily softwoods [13-18]. Counter arguments by the pulp and paper industry focus on the need for valuing and managing forest lands for sustainable production of fiber, lest these forests are cleared for range or crop lands [19-23].

Paper-based consumer products using crop-based fiber

A database on paper-based consumer products with environmental benefits, including annual crop-based fiber content, is available [14]. For example, Kimberly-Clark has created the GreenHarvest tissue product line with 20% nonwood fiber from straw and bamboo pulp production integrated with the Mobile Mill [24]. Some reports have claimed that paper made from straw fiber has equivalent or enhanced physical properties compared to that made with wood pulp, but most commercial nonwood fiber applications have been in products like molded fiber and tissue where fiber strength has not been a significant requirement. Essity (formerly SCA), a major tissue producer in Europe, recently announced licensing a proprietary wheat straw pulping process to also make products with 20% nonwood fiber [25]. Most straw processes produce a yellow/tan colored fiber that would result in a speckled or low brightness product when mixed with bleached wood fiber. This type of visual product is not deemed acceptable for current U.S. tissue markets.

STRAW PULPING PROCESSES

Table I gives a summary of various wheat straw pulping methods. This table provides the active cooking chemicals, process operating temperatures, retention times, expected process yields, and specific processing issues that need to be considered when proposing one of these processes. General discussion of selected processes will be provided in this section as well as the combined table of pulping operations.

Traditional caustic pulping process

Straw pulp has been a staple of the Chinese pulp and paper industry for several decades. During the first 5 Year Plan, the Chinese government actively and aggressively supported straw pulping. Over the last several years, straw pulping has

Process	Chemical	% Applied on O.D. Biomass	Temperature, °C	Time, min	Fiber Yield, % on o.d. biomass	Processing Issues
Soda	NaOH	12–16	145–165	90–240	30–45	Extremely poor drainage; difficult to wash; high silica content in black liquor results in recovery difficulties.
Soda-AQ	NaOH	12–16	145–165	70–120	35–45	
	AQ	0.03				
Kraft	NaOH+Na ₂ S	12–16	145–165	70–180	35–50	
NACO	Na ₂ CO ₃	23–25	135	90–120	40–45	Expected to use a recovery process to remove silica and recycle the Na ₂ CO ₃ .
	MgCO ₃	1				
	NaOH	6–8				
	O ₂	8 Bar Pressure				
Lime process	CaO	7–10	130–140	180-300	30–35	Paper machine scale is likely.
NSSC	Na ₂ SO ₃	8	170	120	52–55	Mainly suitable for medium grades.
	Na ₂ SO ₃	2–3				
Phoenix	NH ₃ OH or KOH	Estimated at about 5%–10% based on assertion that process uses 25% of virgin chemical hardwood pulp or that total yield can be up to 110%.	90–98	Uses twin screws for processing.	55–60 (if coproduct is included, yield is 95%–110%)	Columbia River represents first commercial installation, which is behind schedule. Care is required for a commercial evaluation, especially around the coproduct sales.
CIMV	H ₂ O	10:1 ratio	90–120	30–120	50–60	Multistage process: water and/or acid pretreatment followed by alkaline peroxide bleaching.
	DTPA	0.2				
	CH ₂ O ₂	0.6				
	CH ₃ COOH	1.7	85	240		
	NaOH	6–8.5				
	H ₂ O ₂	5–6				
	PAA	1				
Hot water	H ₂ O	8:1 ratio	145–160	120–180	65–75	Weak fiber; requires refining to liberate fibers; uses acidic water, as the recycled water picks up acidity from the hemi-celluloses dissolved in solution.
Mechano-chemical	NaOH	2–6	95–98	45–60	70–78	Weak fiber; high power and chemical consumption.
CMP—Refiner	NaOH	3–5	120	60	73–78	Weak fiber.
APMP	Na ₂ CO ₃	6–10	95	30	70–75	Fiber liberation occurs in high consistency refiner following chemical pretreatment; low strength pulp.
	H ₂ O ₂	4				
H.F. Process	NaOH	6–7	95–98	240	75–78	Uses a diffuser in a screw press for pulping; only suitable for corrugating medium.
Tranlin	(NH ₄) ₂ SO ₃	9–13	165–173	160–210	58–68 (if coproduct is included, yield is about 95%)	Sells dust control; soil amendment byproduct for economic return instead of recovery.

AQ = anthraquinone; NSSC = neutral sulfite semichemical; CIMV= Compagnie Industrielle de la Matière Végétale; CMP = chemimechanical; APMP = alkaline peroxide mechanical pulp; H.F. = Hojbygaard Fabrick; NaOH = sodium hydroxide; Na₂S = sodium sulfide; Na₂CO₃ = sodium carbonate; MgCO₃ = magnesium carbonate; O₂ = oxygen; CaO = calcium oxide; Na₂SO₃ = sodium sulfite; NH₃OH = ammonium hydroxide; KOH = potassium hydroxide; H₂O = water; DTPA = diethylenetriaminepentaacetic acid; CH₂O₂ = formic acid; CH₃COOH = acetic acid; PAA = peracetic acid; H₂O₂ = hydrogen peroxide; (NH₄)₂SO₃ = ammonium sulfite.

I. Process conditions associated with various straw pulping processes. Data obtained from references [8,25,27-33,39-42,45-52].

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been in significant decline in China because of the environmental toll associated with the practice. China has been consistently shutting down straw and bagasse pulp mills due to inefficiency and high levels of pollution [25,26]. Traditionally, straw pulping facilities have employed a chemical pulping method where sodium hydroxide (NaOH) and sodium thiosulfate ($\text{Na}_2\text{S}_2\text{O}_3$) were used as cooking chemicals; the resulting black liquor was treated for alkaline- and energy-recovery; and some of the NaOH was recovered with the addition of quicklime. In the bleaching system (washing, screening, and bleaching), ClO_2 was used for bleaching, and the screen rejects were incinerated. Treated wastewater was recycled to make pulp, and the sludge from the wastewater treatment was incinerated. The residues, screen rejects, and sludge were typically incinerated for waste management without energy recovery. Heat and electricity were supplied by a combined heat and power (CHP) plant, in which ammonia and limestone were used to absorb nitrous oxides (NO_x) and sulfur dioxide (SO_2), respectively.

The black liquor from straw has high levels of silica and is often discarded rather than recovered because the high silica content forms a corrosive glass within a recovery boiler and causes premature boiler failure. The high levels of silica and saccharides in straw that dissolve in alkaline black liquor increase the viscosity of the liquor to the point where pulp washing can only remove 80%–85% of the black liquor from the pulp prior to the bleach plant. Washing of straw pulp is typically performed on vacuum drum washers with one-third of the loading factor typically used for hardwood kraft pulps because of this difficulty associated with removing spent chemicals from the pulp. The yield to the mill for chemical pulping of straw, typically 30%–35% on o.d. straw, is known to be cost prohibitive. More sophisticated processes can get the yield over 40%, but never to the 52%–56% for hardwood.

Enhanced chemical pulping process

As a result of the large environmental impact and energy requirements of traditional chemical pulping of straw, new pulping methods were developed to enhance the value of straw as a pulp fiber source. Several different pulping methods have been developed based upon ammonia instead of caustic. Ammonium sulfite, $(\text{NH}_3)_2\text{SO}_3$, is often used as the active cooking chemical and is obtained by reaction of ammonia and SO_2 from the combined heat and power generation (CHP) at the mill. These ammonia-based pulping methods produce plant nutrients that can increase the productivity of soil and reduce the potential harm to soils from sodium in that fertilizer. The $(\text{NH}_3)_2\text{SO}_3$ production also eliminates the use of limestone as part of the scrubbing media required for SO_2 absorption in conventional CHP processes since SO_2 is eliminated from the flue gas. The economics of this approach is dependent upon establishing a year-round market for the plant nutrient [27].

Phoenix pulping process

The Phoenix wheat straw pulping process developed for Columbia Pulp by Sustainable Fiber Technologies (SFT; Renton, WA, USA) is proprietary, but several claims about its advantages provide clues to the nature of the process [28,29]. The claims also point to a more efficient and environmentally favorable process than is commonly used in Asian countries for straw and bagasse to produce fiber [9,28,30,31]. Life cycle analyses that compare wood and nonwood pulp production largely rely on data from outdated nonwood mills in Asia that do not have the benefit of improvements made by SFT [32].

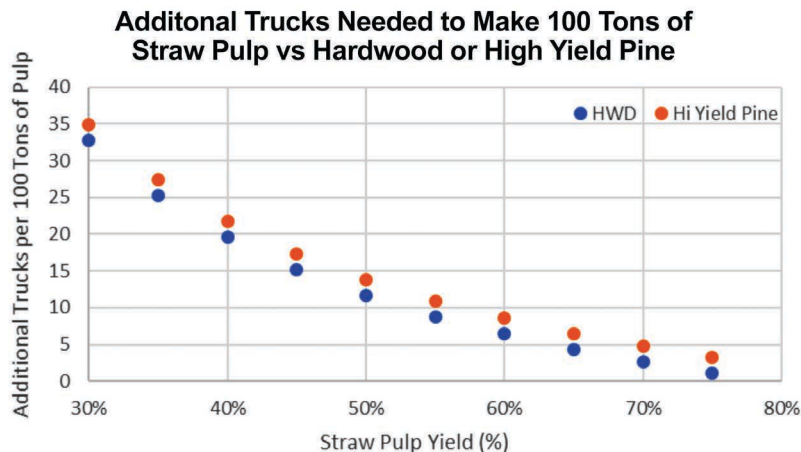
The key environmental claims made by SFT are low water usage (10% of a kraft mill), zero effluent, and use of pulping byproducts as a fertilizer. The use of a mini-mill concept by SFT helps restrict the carbon footprint and economize the utilization of resources [33]. The use of twin-screw extruders to pulp wheat straw under atmospheric conditions at high consistency is seen as a key to low water usage. The use of ammonium sulfite, ammonium hydroxide, or potassium hydroxide as pulping chemicals allows black liquor to be used as a “plant nutrient” [34–36]. Some claims have been made that suggest alkali will be used at the mill instead of an ammonium based chemical. In that event, the “byproduct” liquor will not be able to be employed as a plant nutrient.

While ammonium sulfite can be regenerated by flue gas desulfurization, chemical recovery is generally too costly for small nonwood pulp mills [37]. The high levels of silica in wheat straw present significant challenges in chemical recovery operations [38]. The SFT process has some claims around using calcium salts to precipitate calcium silicate on fiber to mitigate silicate deposits, but the final system is still unknown to the general public.

Traditional kraft mills have the option of selling some of the boiler ash and some of the over-burned lime, but this material is typically discarded in a landfill from concerns about the potential presence of detrimental trace materials. With the conservative nature of the paper industry, there is only a small chance that some companies would opt for selling the plant nutrient produced by these straw pulping methods. Without the ability to sell the “plant nutrient”, the environmental footprint and economics of the straw pulping processes would not be sustainable.

Acid processes

Several acid-based processes have been developed to avoid silicon dissolved in the black liquor. All these acid processes are similar to the Compagnie Industrielle de la Matière Végétale (CIMV; Neuilly-sur-Seine, France) process. The CIMV process uses acetic acid and formic acid as the cooking chemicals [39–42]. The acids dissolve lignins and hydrolyze the hemicelluloses into oligo- and monosaccharides with high xylose content. The raw pulp is filtered, the solvent is removed, and the pulp is bleached with hydrogen peroxide. Organic acids are recycled from the spent pulping liquor via evaporation. Defibration takes place in a subsequent alkaline



1. The number of additional truckloads required to produce 100 o.d. tons of pulp as a function of straw pulp yield. The analysis assumed 18% moisture for straw and 50% moisture for the pine and hardwood chips. The hardwood pulp yield was assumed to be 50% on o.d. wood and the high yield pine yield was assumed to be 56% on o.d. wood. In practice, typical straw yields are less than 50%, thus at least 10 or more additional trucks will be required for each 100 tons of pulp produced.

peroxide bleaching process. The effluents from the mild acid cooking and bleaching stages can be treated in traditional biological wastewater treatment systems. In the case of wheat straw, a pulp with an ISO brightness of over 80% and a yield of over 50% can be obtained with a water-to-straw ratio of 10 and acid charge (25% formic and 75% acetic acid) in hot water of 0–2.3% on the straw. Diethylenetriaminepentaacetic acid (DTPA, 0.2% charge on straw) is used as a chelating agent in these treatments, and the straw is washed and then bleached with a P-P-Paa-P bleaching sequence.

If this type of straw pulp is mixed with a pulp of better quality, the amount of straw pulp substitution is limited to 20%–40% of the mix because of strength requirements. The addition of wheat straw pulp impairs the surface and optical properties, and thus the printability, of the resulting paper. This kind of wheat straw pulp has high bulk and could possibly be used as a raw material for the middle ply of paperboard or for molded fiber packages.

High yield processes

High yield straw fiber may be produced by treatment of the straw with hot water followed by an alkaline peroxide bleaching stage. Typically, the effluent is sewerred, with no liquor recovery, because of the high silicon content of the liquor. This hot water, alkaline peroxide treatment typically produces pulp with 75% yield, like neutral sulfite semichemical (NSSC) hardwood pulp, but more susceptible to process refining and freeness loss [8].

EXAMINATION OF SUSTAINABILITY CLAIMS

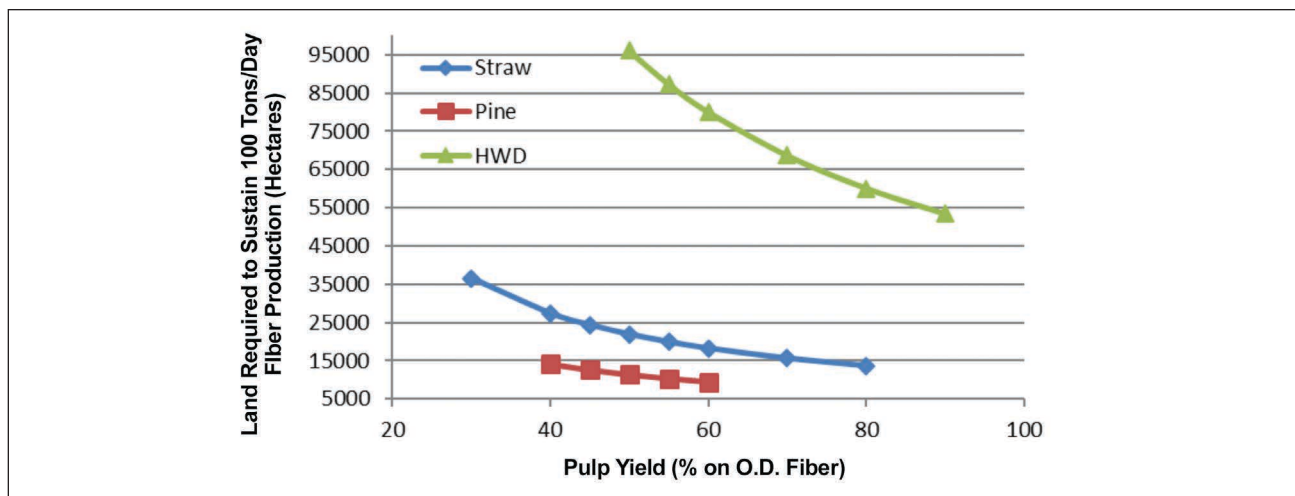
Transportation

One claim that is often made in support of straw pulping is a reduction in raw material transportation because straw mills tend to be small and limit their procurement area to a radius of 125 km or less [8]. While it is true that the economic pro-

curement area for straw is less than 125 km, the packing density of straw is considerably lower than either hardwood or pine pulpwood or chips. As with wood, the total amount of straw required, and hence the number of trucks needed to haul that material, is dependent upon the pulp yield of the cooking method employed. In all cases however, replacing either bleached hardwood pulp or high yield brown pine pulp with straw will result in an increase in the total number of truck-miles required to supply a mill with raw fibrous material. **Figure 1** shows a graph of the increased number of trucks per day required to replace 100 tons per day of o.d. pulp as a function of the straw pulp yield. The limiting factor in hauling straw is the U.S. Department of Transportation (DOT) limits on flatbed trailer length and load height. Many locations in China allow ~80 tons per truck, thus making straw hauling more palatable for a mill. A typical round bale of straw is 5-ft wide by 6-ft diameter with a weight at 18% moisture of about 1100 pounds per green bale. The straw is typically cut and dried in open fields until it dries to about 18% moisture or less. If the straw is baled at higher than 18% moisture, significant microbial action can occur, resulting in heat generation, straw degradation, and potential fires within the straw bale. These bales would be either left in the field, moved to the edge of the field or moved into a storage facility on a flatbed truck.

The DOT requirements limit flatbed truck trailer to 40 ft long and total height of 13 ft 6 in. and may limit width to 8 ft 6 in. It is possible to stack up to 14 round bales per truckload. Using the 14-bale restriction, each truckload will carry about 6.3 o.d. tons (7.7 green tons) of straw per load. Depending upon height limitations, it may be possible to stack an additional 5 bales on top of the first layer and increase the total green weight to 10.45 tons at 18% moisture, which equates to 8.57 o.d. tons of straw per load. In contrast, wood chip-loaded tractor trailers can go to 80000 lb. Typical

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2. Land required to sustainably support 350000 tons/year production of pulp.

empty weight is 35000 lb, and typical load weight is 40000 lb, which equals 20 tons of green chips or 10 tons of o.d. chips. Assuming a 50% pulp yield for hardwood and a 56% yield on o.d. wood for high yield pine, more trucks will be required for straw pulping at any commercially obtainable straw pulp yield.

Land requirements and availability

Another claim often made about straw pulp is a reduction in the amount of land required to support a mill [6]. As with the trucking data, the amount of land required is dependent upon the pulp yield. For all cases, high yield pine requires less land to obtain a sustainable growth rate than straw, and hardwood requires more land. The sustainable growth values for pine and hardwood in the coastal Virginia-Carolina region were obtained from WestRock Forestry and were reported as 5 green tons/acre-year for plantation pine and 0.59 green tons/acre-year for natural mixed southern hardwood. The reported values for straw are 1.57 green tons/acre-year. **Figure 2** shows the land required to support 100 tons/day of pulp production for a 350 day per year operating rate for all three fibers. This analysis simply looks at the required amount of land. It does not evaluate whether the land is under plantation management for growing trees, under management for growing wheat and straw as a side benefit, or wild management

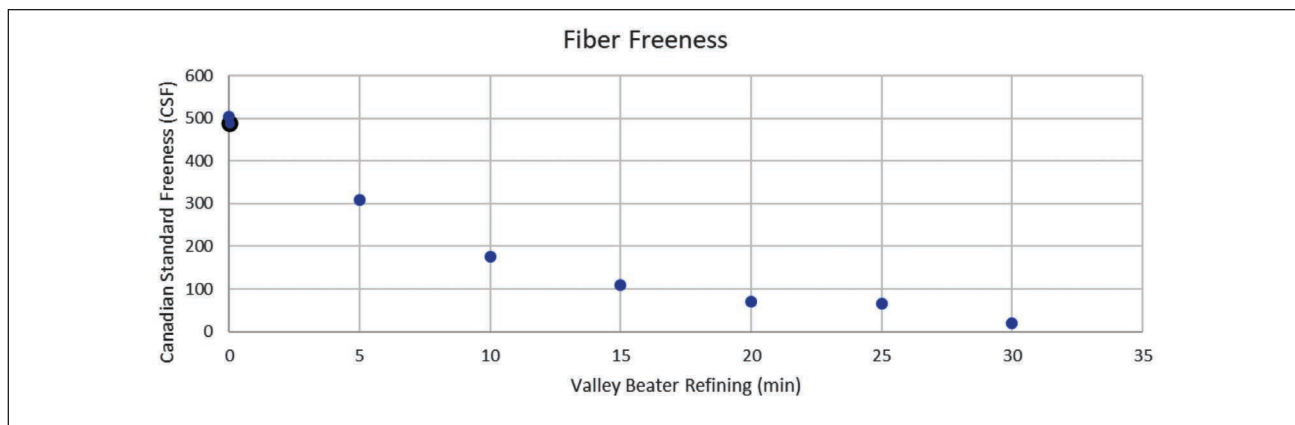
for growing hardwoods. Typically, a mill will have to incentivize farmers to supply straw, so some mills may have to supply their own fiber regardless of the crop being maintained on the land.

Traditionally, some of the straw is incorporated back into the field as a natural form of fertilizer. The National Renewable Energy Laboratory (NREL) has estimated that some fertilization will be required to overcome the removal of straw to make pulp. These fertilizer requirements are over and above the amount required to produce a wheat crop and only account for the lost nutrients associated with the straw removed. These requirements are based upon tons per acre of applied fertilizer. The annual requirements to replace the straw nutrient values are 9.8 kg of nitrogen, 54.3 kg of potassium oxide, and 3.0 kg of phosphorous per acre [43].

In addition to the land requirements for a theoretical mill, the availability of raw material for straw pulp production is somewhat limited. Winter wheat agricultural activity does have a presence in the Carolinas and Eastern Virginia, with a reported 1,275,000 acres harvested in 2012. On a crop production basis, this puts the Virginia-Carolina region at 45% of the United States winter wheat production, with the majority in the more Western states, such as Kansas, Oklahoma, Montana, Colorado, Texas, Washington, South Dakota, and Nebraska, with some major production along the Mississippi river valley.

State	Acres of Land in Winter Wheat	Available Straw at 3000 lb/acre, tons	25% Straw Removal Rate, tons	Tons Straw Pulp at 50% Pulp Yield, o.d. tons pulp
South Carolina	235000	352500	88125	44062
North Carolina	770000	1,115,000	288750	144137
Virginia	270000	405000	101250	50625
Regional Total	1,275,000	1,872,500	478125	239062

II. Estimated annual tons of winter wheat straw pulp available in the Virginia-Carolina region. Data based on National Agricultural Statistic Service (NASS) Crop Production Report released 10 August 2012 [44].



3. Freeness as a function of time in the Valley beater.

For the Virginia-Carolina region, the total amount of straw available is limited to an equivalent of 239000 tons/year of pulp if one assumes no other competitive pressures and no loss of material associated with degradation of raw materials during the year-long storage required for the annual crop material. The total pulp production number was obtained by using the acres of wheat planted according to the National Agricultural Statistic Service (NASS) Crop Production Report released August 10, 2012, and assuming an availability of 1.5 tons/acre of straw [44]. It was assumed that 25% of the available straw could be successfully removed from the field and successfully processed in a mill. A 50% pulping yield was also assumed. The detailed numbers for the Virginia-Carolina region are shown in **Table II**.

PHYSICAL PROPERTIES

Several studies have suggested that straw pulp can be used as a replacement for hardwood up to potentially 30%–40% of the fiber. Other studies have claimed that straw fiber might enhance some of the strength properties of the resulting sheet. In general, the current commercial applications using straw pulp are tissue or molded pulp applications that do not demand significant fiber strength.

In order to determine the impact of straw fiber on resulting sheet properties, a sample of Columbia Gold Unbleached Wet Lap Wheat Straw Market Pulp was obtained and beaten in a valley beater at WestRock's Richmond pilot plant in Virginia. The freeness of the straw pulp started at 505 CSF and rapidly decreased with beating. The freeness curve as a function of time in the valley beater is shown in **Fig. 3**. The rapid decrease in freeness suggests that straw pulp needs to be handled carefully under industrial conditions, as excessive pumping and mixing will be enough to lower the freeness of the straw pulp, potentially resulting in drainage problems on the wet end of the paper machine. The straw fiber is thin walled and fractures quite easily. Pumping and blending will result in freeness loss. Also, the use of white water from a system containing straw pulp will load the system with excessive fines, also resulting in extremely low freeness and poor wet end drainage.

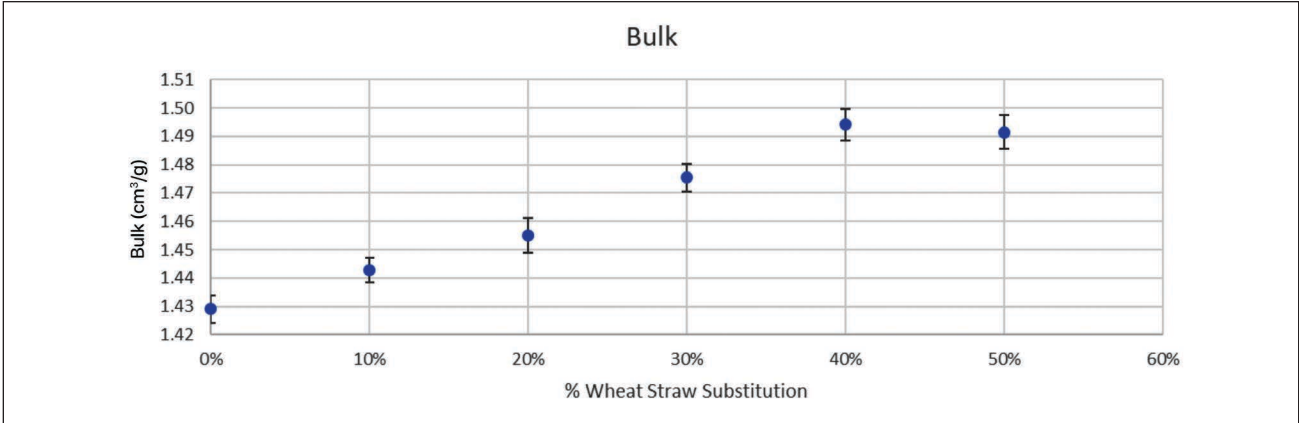
Handsheet Set #	Softwood, %	Hardwood, %	Straw, %
1	50%	50%	0%
2	50%	40%	10%
3	50%	30%	20%
4	50%	20%	30%
5	50%	10%	40%
6	50%	0%	50%

III. Composition of tested handsheets.

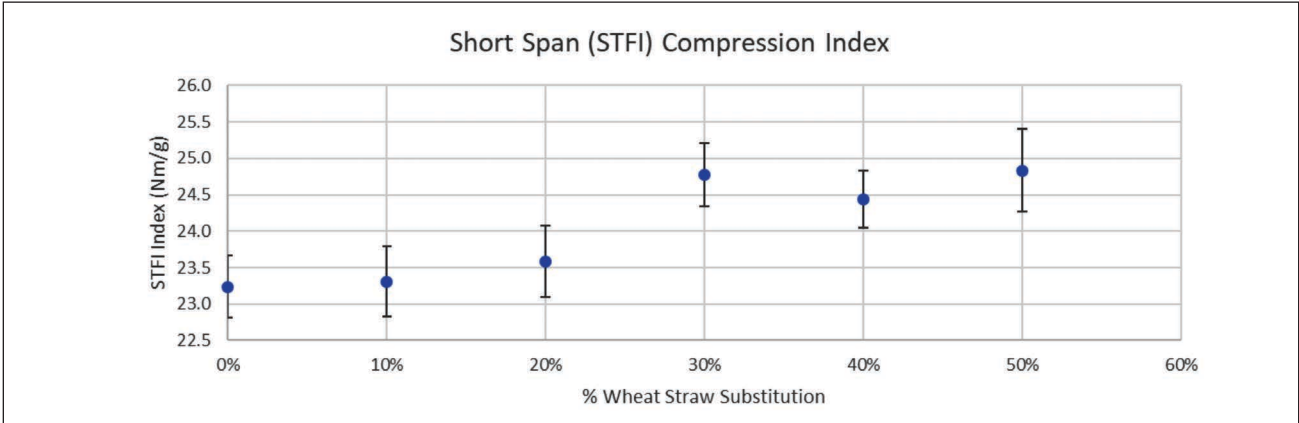
Bleached board handsheets

Two sets of 120-g/m² handsheet studies were conducted using straw pulp. Both studies used unrefined fiber as received in wet lap form, without refining as board grades are typically refined to about 550 mL CSF for machine operation. As the unrefined straw pulp is already lower than 600 CSF, it was determined that no additional refining was warranted. One set of handsheets used 50% bleached softwood fiber refined to 550 mL CSF and a sample of unrefined wheat straw pulp (505 CSF) substituted for bleached hardwood beaten to 550 CSF in 10% increments from 0 to 50% of the sheet. The composition of these handsheets is shown in **Table III**. These handsheets were tested for physical properties. **Figures 4, 5 and 6** show the impact of straw fiber substitution on bulk, STFI, and burst, respectively. Figure 4 shows that the addition of straw pulp enhances bulk, with a steady increase up to about 40% substitution. After the 40% level, the bulk levels off. Figure 5 shows that substituting a portion of straw pulp for hardwood has little impact upon the STFI until the substitution level is increased to 30% of the sheet. Once the straw content of the sheet reached 30%, the STFI increased by roughly 5%. Finally, the burst index (Fig. 6) increased by about 6% with the addition of as little as 10% straw pulp. The burst index values were somewhat erratic and need to be carefully viewed.

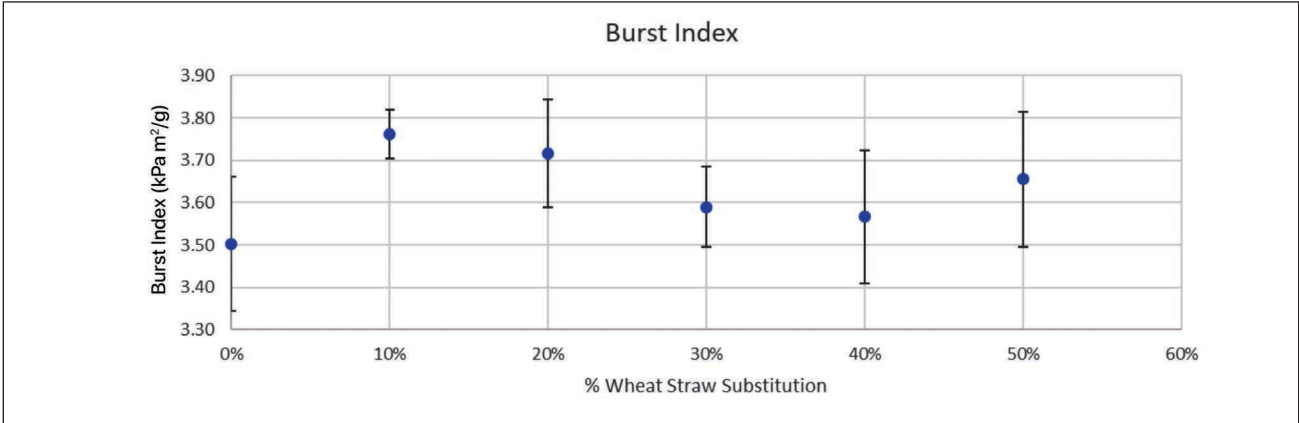
Stiffness, tear, and Young's modulus were also measured as a function of straw pulp substitution for hardwood. In all cases, the addition of straw in any amount resulted in decreased property performance for these physical properties.



4. Impact of straw pulp substitution for hardwood on handsheet bulk.



5. Impact of straw pulp substitution for hardwood on STFI.



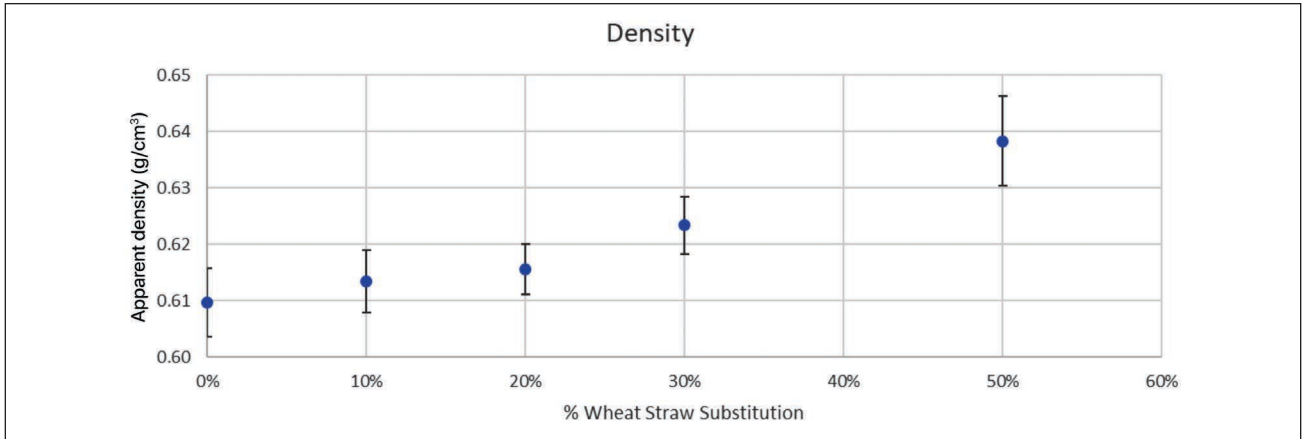
6. Impact of straw pulp substitution for hardwood on burst index.

Linerboard handsheets

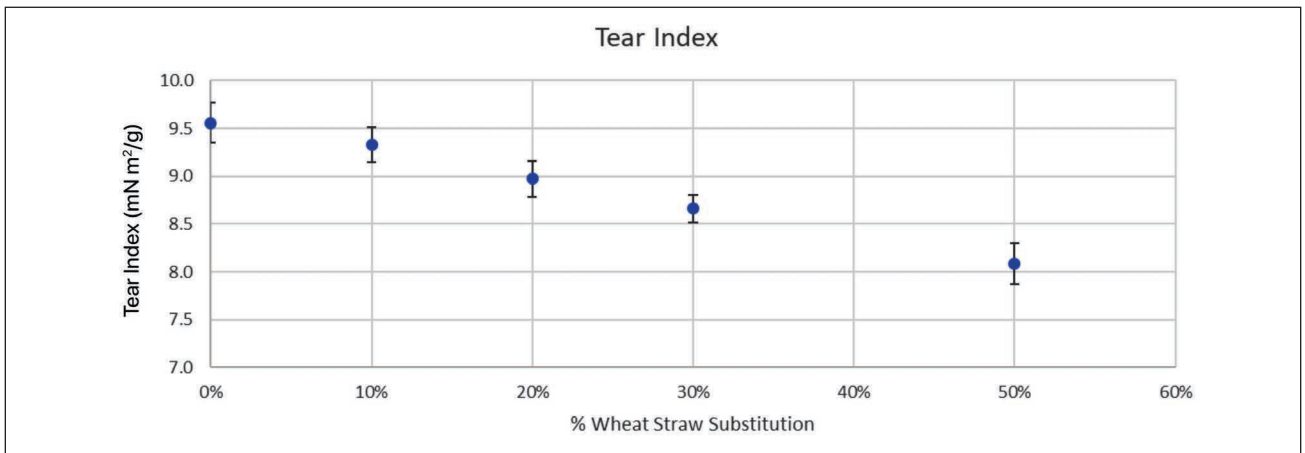
The second set of 120-g/m² handsheets employed 106 kappa number high yield pine pulp refined to 620 mL CSF with unbleached straw pulp (505 mL CSF) substituted in 10% increments from 0 to 50% of the sheet. As the percentage of straw pulp increased, the handsheet density increased (**Fig. 7**). Tear (**Fig. 8**), tensile (**Fig. 9**), and burst (**Fig. 10**) also decreased with increasing straw substitution. Short span compression (**Fig. 11**) showed a very slight increase with increasing straw substitution.

CONCLUSIONS

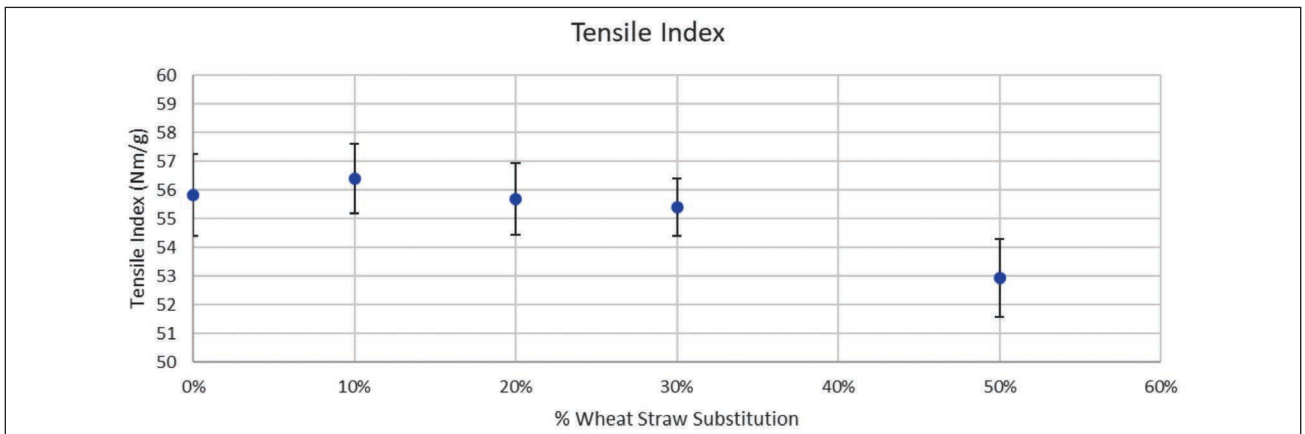
From a sustainability or environmental perspective, the use of straw pulp as a replacement for kraft pulp is of limited value. Each situation needs specific and direct comparisons that are not generally available. If details of various novel processes, such as the Phoenix pulping process, become public, a more relevant and modern comparison can be made. Claims around reduced transportation requirements or reduced land impact requirements are not strongly substantiated upon close examination. Using straw



7. Impact of straw pulp substitution for high yield pine pulp on resulting handsheet density.



8. Impact of straw pulp substitution for high yield pine pulp on tear index.

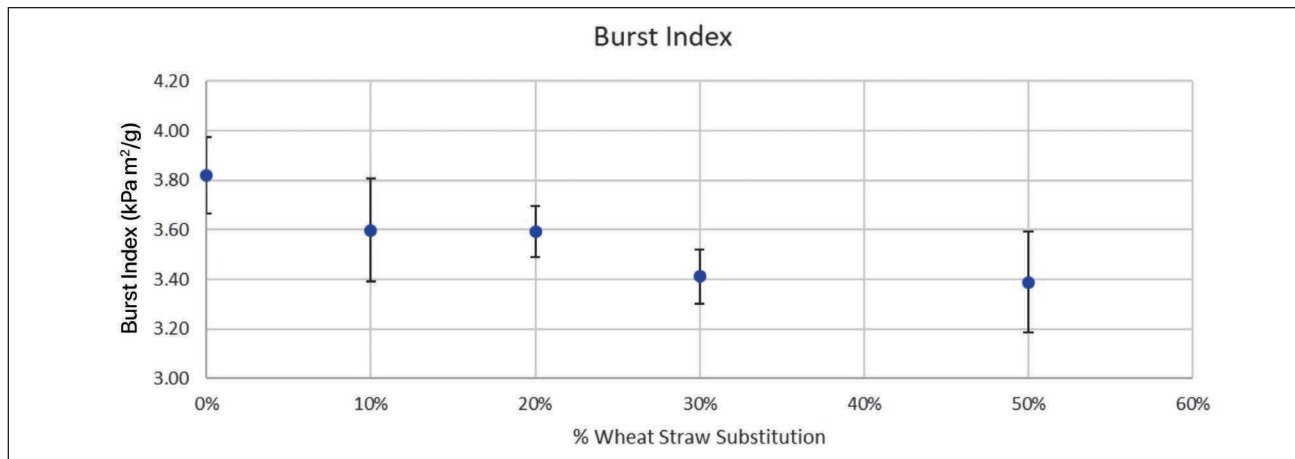


9. Impact of straw pulp substitution for high yield pine pulp on tensile index.

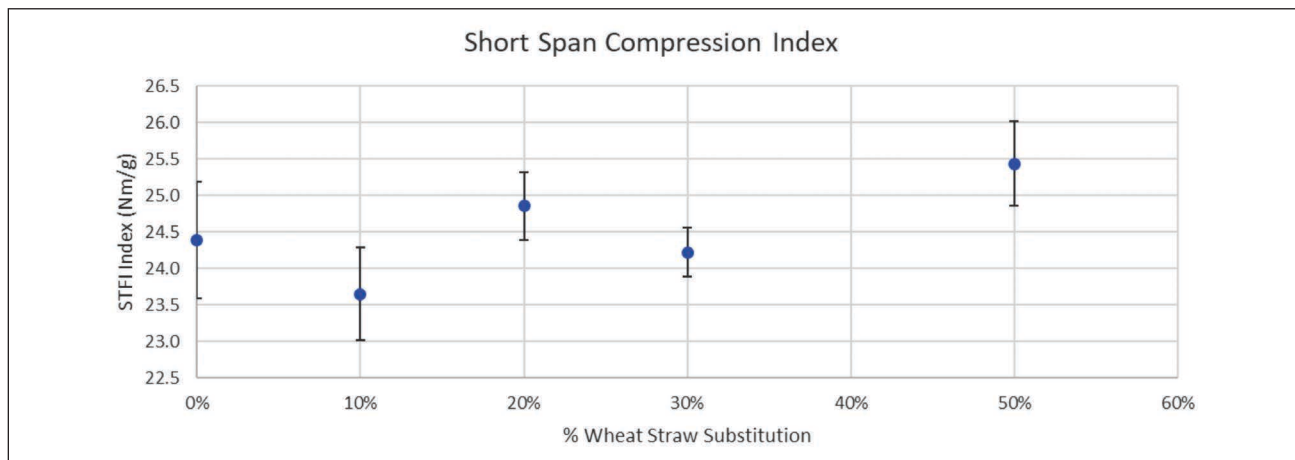
fiber will increase the amount of truck traffic entering the mill. Substituting straw pulp for high yield wood pulp will increase the amount of land required to support sustainable plantation growth. For the same amount of pulp fiber, straw pulp requires less land than mixed southern hardwood stands require.

The handsheet studies showed limited to negative value of straw pulp substitution for high yield pulp, and this is a best-

case analysis, as straw fiber fractures due to normal pumping and blending. The fracture case was not duplicated in these studies. Some improvements in selected strength properties might result from partial substitution of straw for bleached hardwood fiber. In general, straw fiber can be partially substituted for hardwood fiber in low strength applications, such as in tissue and molded fiber applications. The economics,



10. Impact of straw pulp substitution for high yield pine pulp on burst index.



11. Impact of straw pulp substitution for high yield pine pulp on short span compression index.

transportation, year-long storage, and sustainability difficulties associated with using straw as a fiber source still require greater study before straw pulp will become a reliable alternative fiber source for more than specialty applications. **TJ**

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ABOUT THE AUTHOR

WestRock is interested in sustainable papermaking. Several news articles have suggested that the use of annual crop fiber is as or more sustainable than using wood fiber. The current work evaluated these claims and also evaluated the suitability of wheat straw pulp as a partial wood fiber replacement in traditional packaging materials.

The current work evaluated several life cycle analyses (LCA) that have been conducted both in favor or and against annual fiber crops as fiber sources. It reviews several assumptions that impact these analyses (both positive and negative).

LCA are extremely sensitive to the starting and ending conditions used for a comparison. There are several ways to make an LCA appear better or worse than it actually is, and interpretation of LCA data must be done carefully to fully understand the value they offer.

Obtaining a sample of straw pulp for laboratory analysis was the most difficult part of the current work. A surprising finding was the lack of availability of annual crop fiber. If only a few mills started using

wheat straw at a low substitution rate, it would wipe out the total potential supply of the entire Coastal Plain region. The lack of infrastructure to collect, store and process these annual crop fibers is also woefully inadequate for a typical packaging mill's needs.

The current work outlines several operational issues that need to be addressed before using an annual crop fiber. The physical property evaluation suggests that wheat straw fiber would be good for tissue and towel applications, but poor for inclusion in traditional packaging grades. We will continue to monitor the developments in annual crop processing and re-evaluate as processes improve.



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