ASSESSMENT OF COMBINED STRAW PULP AND ENERGY PRODUCTION

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The aim of this study was to evaluate the potential of a new, straw-based fibre manufacturing technology integrated to bioenergy and biofuels production. The process is based on a novel hot water treatment and subsequent mechanical refining, both of which are performed at a high temperature. Soda process, ethanol production, and chemical defibration based on hot water treatment and subsequent alkaline peroxide bleaching were selected as references. The idea is to utilise the fibre fraction for packaging and the dissolved solids and the formed fines for energy. The investment costs of this process are significantly lower than those of a soda process. Additionally, a chemicals recovery process is unnecessary. Furthermore, the process offers an attractive alternative for biogas production. However, the assessment showed that the process could only be economical in some terms. Subsidies for investment would probably be needed to promote the acceptance of this environmentally safe process.

Keywords: Non-wood fibre; Wheat straw; Biorefinery; Hot water treatment; Mechanical refining; Assessment; Pulp; Energy

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INTRODUCTION

Non-wood pulping processes are typically chemical or chemi-mechanical processes (Leponiemi 2008). Up to now, very few results of pulp properties from non-wood based mechanical pulp without chemical impregnation have been reported. Extrusion pulping process is one of the rare processes that has been mentioned for the processing of non-woods such as bast fibres without chemicals (van Roekel et al. 1995). However, hemp bast fibres differ significantly from short fibre non-wood raw materials, such as wheat straw. The lignin content of bast fibres is significantly lower and the fibres are extremely long. The mechanical fibres are usually stiff, coarse and straight. In addition, fines are formed during refining. Therefore the strength properties of mechanical pulps are lower than those of chemical pulps.

The results of our previous research have shown that it is possible to produce pulp from wheat straw by a simple procedure based on a hot water treatment and subsequent mechanical defibration (Leponiemi et al. 2010). In this paper this process is referred to as the "mechanical" approach. The novelty of the process comes from the idea of utilising the reject material not suitable for pulp fibre, such as dissolved solids or fines, for energy production. The drainability of the produced pulp was good, but the strength properties were low (Leponiemi et al. 2010).

Wood-based mechanical pulping research indicates that by increasing the refining temperature, the energy consumption in refining is reduced and mechanical pulp properties are maintained or even improved, but the optical properties are reduced. (Muenster 2005; Nurminen 1999; Höglund et al. 1994, 1995; Sabourin et al. 1996). Therefore, it was thought worthwhile to investigate the possibility of improving the mechanical wheat straw pulp properties and reducing energy consumption in refining by the use of elevated temperature in hot water treatment and mechanical refining. The bonding properties of the fibres may be improved simultaneously.

A hydrothermal pretreatment of lignocellulosics is known to enhance both bioethanol and biogas production. Since such a treatment of straw material is similar in fibre and energy production, the aim of this work is to investigate the synergistic benefits of combining fibres and energy production from wheat straw. The assumption is that mechanical pulp with adequate quality for packaging can be produced by conventional refining equipment at high temperature, while the residue can be utilized for energy production.

The aim of this work was to determine the potential and estimate the cost level of the suggested process. Soda pulping, ethanol production and chemical pulping process, including hot water treatment and the subsequent alkaline peroxide bleaching (Leponiemi et al. 2010; Mustajoki et al. 2010) were selected as the references for the suggested process. In this paper the chemical pulping process is referred to as the “chemical” approach.

EXPERIMENTAL

Mechanical Refining Experiments at High Temperature

Raw material

Air-dried wheat straw was used as a raw material for the experiments. The straw was cultivated in Jokioinen, Finland and harvested during the summer of 2007. The straw was chopped at the end of the threshing machine, air dried, and stored in an unheated barn for about two years. The fines were removed by using a screen described in the standard SCAN-CM 40:88. The diameter of screen holes was 6 mm and the screening time was 30 s. The dry matter content of the screened straw was determined according to the standard SCAN-CM 39:88.

Hot water treatment

The hot water treatment was performed in 2.5 L autoclaves of an air-heated rotating digester. The hot water treatment temperature was 170 °C, the time 45 min, and the water to straw ratio 10:1. Deionised water was used, and no chemicals were added in the treatment.

The treated straw was then washed by diluting it with deionised water, agitating, leaving the mixture to settle for 2, minutes and removing the excess water through a wire pouch. Dilution and thickening were repeated 3 times. Finally, the washed straw was centrifuged to 25% consistency.

Mechanical refining

The batch type wing defibrator at Aalto University, in the Department of Forest Products Technology, was used for the refining experiments at 170°C temperature. The refiner was first preheated with direct steam to 170°C. Then the hot water treated straw was placed in the lockers between the blades and the cover was closed. The refining was started by preheating the straw with direct steam for 5 min, during which the blades were rotated a couple of times manually to ensure even heating. After the heating, the motor of the defibrator was started. The amount of straw used in refining was 75 g abs. dry. The refining time was 2 to 4 s, the speed of rotation 60 r/min, and the distance between the stator and the rotor 1 mm. The very short refining time and the relatively wide distance between the blades caused a somewhat inhomogeneous refining result, as part of the straw remained unrefined.

Analysis

Before preparing the handsheets according to the ISO 5269-1 test method, the refined pulp was wet-disintegrated according to the method ISO 5263 and screened on a Mänttä flat screen using a screen plate with a slot of 0.25 mm. Laboratory hand sheets were prepared, and paper technical properties were measured according to following test methods: bulk ISO 534:2005, tensile and strech ISO 1924-2, and Scott Bond TAPPI UM-403. The pulp was fractionated with a Bauer McNett apparatus according to SCAN-CM 6:05. The plates used were 16, 30, 100, and 200 mesh.

Assessment of Process Concept

Production

The production level was estimated for a mill utilising 100,000 tonnes of dry wheat straw. The yield of soda pulping in the calculation was 40% (Savcor Indufor 2007), the yield of ethanol production 19% (von Weymarn 2007) and the yield of chemical approach by a hot water treatment and the following alkaline peroxide bleaching 55% (Leponiemi et al. 2010; Mustajoki et al. 2010). The ethanol amount was converted to liters using a density value of 0.79 g/cm^3.

The yield of biogas production from dissolved solids and fines from the high temperature mechanical pulping process was derived from the experiments of Kaparaju et al. (2009). They performed a hydrothermal pretreatment at 180 to 190°C temperature for about 20 min. The biogas yield was 384 m^3/tonne hydrolysate or 386 m^3/tonne remaining solids fraction (Kaparaju et al. 2009). These pretreatment conditions resulted in a 25% dissolution of straw during this stage. Thus, the biogas yield results were assumed to be relevant for our study, and the biogas yield in it was assumed to be 385 m^3/tonne of dissolved solids or fines. The energy content of biogas is 6 kWh/m^3 (Härkönen 2008). In the "chemical" approach, only the dissolved solids from hot water treatment and the first alkaline peroxide bleaching stage are assumed to be exploitable for biogas production.

Pulp, ethanol, and biogas prices

Straw pulp is not sold in the region's commercial markets. Thus straw pulp prices were estimated based on hardwood kraft pulp prices. Savcor Indufor (2006) used an estimate of 20% lower market price for straw pulp than for corresponding hardwood market pulp in China. According to FOEX indexes Ltd., the price of hardwood kraft pulp in October 2010 was 617.5 EUR/ADt and the price of recycled fibres (OCC) was 120.2 EUR/ADt (FOEX 2010). Therefore, a reasonable estimate for the price of bleached straw soda pulp could be approximately 400 Eur/ADt and the price of the pulp produced by the "chemical" approach could be 350 Eur/ADt since the lower brightness may decrease the pulp price slightly. The price of unbleached mechanical straw pulp is estimated to vary between 150 and 250 Eur/ADt. The price spread was estimated from the fluctuation of recycled fibres price and the possible price increase of recycled fibres in the future.

Biogas prices were estimated according to current prices of natural gas and the current premium prices in some European countries where the green certificate or feed-in tariff is promoting the market introduction of green bioenergy. The biogas price is estimated to vary in the range 30 to 60 Eur/MWh.

The ethanol price was determined according to the price of Brazilian sugarcane ethanol imported to Europe and the prices of ethanol produced from renewable sources. Due to the directive on the promotion of energy from renewable sources in Europe, additional benefit is obtained when producing ethanol from wastes and residues. This next generation ethanol can be double-counted in the national quota to transportation fuels. Hence the ethanol price is estimated to vary from 0.65 to 0.98 Eur/L.

Investment costs

The soda mill investment costs were assumed to be approximately the same as the kraft mill investment costs. In this study, the investment costs of the soda pulp mill were estimated to be 1700 Eur/ADt. The investment costs of the "chemical" approach were estimated to be 60% of those in the soda pulping due to the lack of chemical recovery.

The investment costs of the "mechanical" approach (unbleached pulp and energy) were estimated to be clearly lower than those of soda or "chemical" approach. The costs for the "mechanical" option were estimated from the prices of a saw dust digester, a TMP reject grinder, two-phase pressurised screens, and a biogas plant. In addition, the costs of building, engineering, and contingencies were added to the expenses.

The investment costs of a bioethanol plant using 100 000 tonnes straw were estimated based on the costs of a bioethanol plant using 160 000 tonnes straw (von Weymarn 2007) as follows,

$$I = I_{(\text{von Weymarn})} * (P / P_{(\text{von Weymarn})})^{0.7} \quad (1)$$

where I represents the investment costs, $I_{(\text{von Weymarn})}$ is the investment cost for a 160,000 tonnes plant (110 MEur), P is the production rate for 100,000 tonnes dry straw/a, and $P_{(\text{von Weymarn})}$ is the production rate, for 160,000 tonnes dry straw/a. The annual instalment of investment costs were calculated for 10 year period and the interest rate was 5%. The repayments were assumed to be equal for each year.

Production costs

The variable production costs were estimated according to West European cost level. The price of wheat straw in this calculation was 52.3 Eur/t (von Weymarn 2007). The soda mill production costs were assumed to be approximately the same as the kraft mill production costs. Staff costs were assumed to be 40 Eur/ADt for every pulping process. Maintenance costs of a biogas plant were estimated to be 15 Eur/MWh.

The chemical costs in the "chemical" process option were estimated based on the chemical consumptions from earlier research: 9% NaOH, 5% H_2O_2, 1% peracetic acid on dry straw (Leponiemi et al. 2010) and the following chemical prices/tonne of 100% chemical (Pirneskoski 2010): sodium hydroxide 250 €, hydrogen peroxide 475 € and peracetic acid 1850 €.

In the "mechanical" and "chemical" approach the required heating energy (kWh/ADt) of hot water treatment was calculated as follows,

$$Q = (1-\varepsilon) * \dot{m}_w * C_p * \Delta T / 3600 \quad (2)$$

where ε is the heat recovery factor, $\dot{m}_w$ is the water amount (kg), cP is the specific heat (4.19 kJ/kg°C), and ΔT is the temperature difference (°C).

The water amount was calculated as follows,

$$\dot{m}_w = \dot{m}_s * (W:S) \quad (3)$$

where $\dot{m}_s$ is the straw amount (kg/ADt) and W:S is the water to straw ratio (kg/kg).

In the calculation, the initial temperature of the water was taken to be 40°C, the heat recovery factor 50%, and the water to straw ratio 5. The received value was multiplied with the energy cost of 30 Eur/MWh. The calculated heating energy for hot water treatment was then added to the soda pulping energy costs. The reason for adding the heating energy costs to the soda pulping energy costs was the assumption that soda cooking consumes no energy, since the energy is produced in chemical recovery and therefore the energy consumption of a soda process comes from other sub processes. It was further assumed that the energy consumption of other sub-processes in both "mechanical" and "chemical" approach is approximately at the same level as in the soda process.

RESULTS AND DISCUSSION

A Novel Combined Mechanical Straw Pulp and Energy Process

Previous work showed that straw pulp can be produced by hot water treatment followed by mechanical refining (Leponiemi et al. 2010). The dissolved solids and fines which hamper drainability can be utilised for energy production. The strength properties of the produced pulp were low. By further increasing the hot water treatment and refining temperature, it is possible to improve the pulp properties, as Table 1 indicates. These preliminary results show the potential of this process. The process is very simple; it requires only hot water and some mechanical energy. The straw almost defibrates by itself at 170°C; hence the mechanical energy requirements are low. The properties of such pulp are quite reasonable and therefore suitable for fluting. By an alkaline peroxide treatment, the pulp properties can be improved slightly, if needed.

Table 1. Pulp Properties of Mechanically Refined Hot Water Treated Wheat Straw. HWT and Refining Temperature 170 °C

HWT and refining temperature	120 °C (Leponiemi et al. 2010)		170 °C		
	Mechanically refined wheat straw	Alkaline peroxide treatment after mechanical refining	Mechanically refined wheat straw*		Alkaline peroxide treatment after mechanical refining
Bulk, m^3/t	4.2	3.1	2.6	2.6	2.6
Tensile index, Nm/g	4.6	19.2	24.6	22.0	30.1
Stretch, %	1.5	2.1	1.3	1.4	2.0
Scott Bond, J/m^2	44	95	141	122	188

* Parallel testpoints

At 170°C temperature, 30% of the straw solids were dissolved by the hot water treatment (Fig. 1). According to the Bauer-McNett fractionation, the fines content of the produced pulp was 25%. Part of the straw remained without mechanical refining effect due to the wide gap between the refiner blades. Based on the earlier results (Leponiemi et al. 2010) the fines amount would probably increase 5 to 10% if the straw was totally defibrated.

The dissolved solids and the formed fines can be used for energy production. Ethanol production could be one possibility if an ethanol plant was located close to the fibre mill. The dissolved solids and fines could presumably be utilised without a steam explosion stage, which is usually required as a pretreatment for lignocellulosics prior to fermentation. If an ethanol plant was not close to the mill, a biogas production through anaerobic digestion would be another option. In such a case the hot water treatment and mechanical refining at high temperature could presumably replace the hydrothermal pretreatment stage typically required prior to the anaerobic digestion of straw.

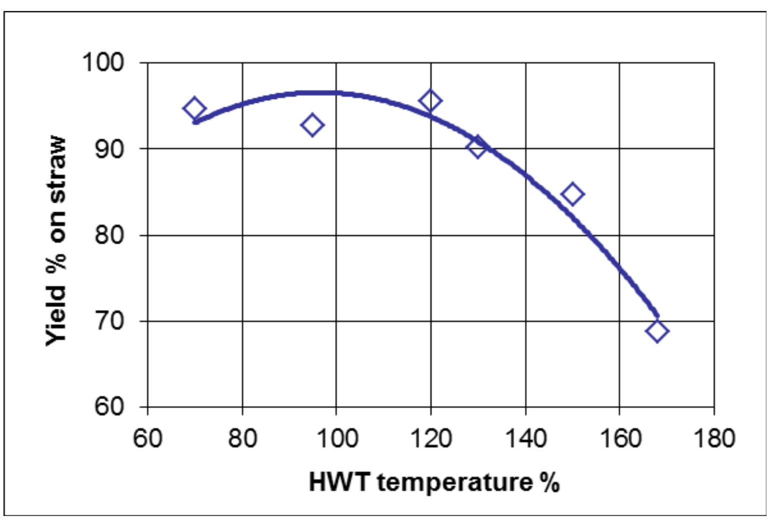

Fig. 1. Effect of hot water treatment temperature (HWT) on wheat straw yield

Prefeasibility Study of Combined Pulp and Energy Production

The proposed "mechanical" process concept based on a hot water treatment and subsequent mechanical refining at high temperature could be an option for fluting production. The "chemical" approach based on a hot water treatment and subsequent alkaline peroxide bleaching (Leponiemi et al. 2010, Mustajoki et al. 2010) could be an option to replace bleached chemical pulps if very high brightness values are not required. In both approaches, the lower quality material, such as dissolved solids or fines, could be used for energy production. Soda process and ethanol production from straw were selected as reference points.

Due to the logistics involved in the use of wheat straw, the processes were restricted to approximately 50,000 ADt soda pulp/a, which means 100,000 tonnes of dry straw. The costs of the processes depend highly on the local conditions and the equipment selected. Furthermore, the prices of products depend on the market situation, and especially on the demand for the product in question. Therefore an exact evaluation is difficult to present; hence the aim of this assessment is to determine the potential of the suggested process.

Table 2 presents the pulp bioethanol and biogas production volumes from 100 000 BDt straw supply and the prices of the corresponding products. The prices are estimated according to the West European price level. The fibre losses in raw material handling and in process are assumed to be the same; thus they are not included in the assessment.

The investment costs of the "chemical" approach were estimated to be 60% lower from those of the soda pulping due to the lack of chemical recovery. The investment costs of the "mechanical" approach were estimated to be clearly lower than those of soda or "chemical" approach due to the much simpler process without chemical recovery and bleaching plant. The investment costs of a bioethanol plant were estimated to be about the same as a soda pulp mill.

Table 2. Pulp, Bioethanol and Biogas Production and Estimated Income. Straw Supply 100,000 BDt/a

	Soda	**"Mechanical"**	**"Chemical"**	**Bioethanol**
References	(Savcor Indufor 2007)		Leponiemi et al. 2010	(von Weymarn 2007)
Pulp production ADt	**44400**	**44400**	**61100**	**0**
Bioethanol production, m^3				**24050**
Biogas - production,million m^3 - production MWh/a		 **23.1** **138600**	 **9.6** **57800**	
Prices - straw pulp Eur/ADt - ethanol, Eur/l - biogas, Eur/MWh	 **400** 	 **150-250** **30-60**	 **350** **30-60**	 **0.65-0.98**
Income - pulp, MEur/a - bioethanol, Eur/a - biogas, Eur/a - Total, MEur/a	 **17.8** **17.8**	 **6.7 – 11.1** **4.2 – 8.3** **10.9 – 19.4**	 **21.4** **1.7 – 3.5** **23.1 – 24.9**	 **15.7 – 23.6** **15.7 – 23.6**

The main variable production costs of pulp include raw material, chemicals, and energy. The most significant difference in production costs of a straw pulping process compared with the traditional wood based pulping processes comes from raw material costs. The soda mill production costs were assumed to be approximately the same as the kraft mill production costs. Table 3 presents the cost estimates for pulp and bioethanol production. The values are estimated according to West European cost level (Suhonen 2010).

Table 3. Cost Estimates for Pulp or Bioethanol Production. Straw Supply 100,000 BDt/a

Process Pulp production ADt/a	**Soda** **44400**	**"Mechanical"** **44400**	**"Chemical"** **61100**	**Bioethanol**
Investment costs, MEur	**75**	**23**	**45**	**79**
Production costs, Eur/ADt				
- raw material	**118**	**118**	**86**	
- chemicals	**38**	**0**	**118**	
- energy	**36**	**62**	**47**	
- personnel	**40**	**40**	**40**	
- sum	**232**	**220**	**291**	
Production costs MEur/a	**10.3**	**9.8**	**17.8**	
Biogas maintenance costs, MEur/a		**2.1**	**0.9**	
Bioethanol production costs				
- Eur/l				**0.55**
- MEur/a				**13.2**
Total production costs, MEur/a	**10.3**	**11.9**	**18.7**	**13.2**

Comparison of Processes

Table 4 presents the economical comparison of the selected processes. The bioethanol production from straw is not profitable due to the high investment and production costs (von Weymarn 2007), unless the price of the produced bioethanol is significantly higher than the price of the Brazilian sugarcane ethanol. The combined production of fibres and energy by the suggested "mechanical" approach is projected to have notably lower investment costs than the soda process or a bioethanol plant. However, the value of produced unbleached pulp is lower.

Table 4. Profitability Calculation of Processes

Process	**Soda**	**"Mechanical"**	**"Chemical"**	**Bioethanol**
Income, MEur/a				
- pulp	**17.8**	**6.7 – 11.1**	**21.4**	
- biogas		**4.2 – 8.3**	**1.7 – 3.5**	
- ethanol				**15.7 – 23.6**
- sum	**17.8**	**10.9 – 19.4**	**23.1 – 24.9**	**15.7 – 23.6**
Costs, MEur/a				
- interest (5%)	**3.8**	**1.2**	**2.3**	**4.0**
- instalment (10 years)	**7.5**	**2.3**	**4.5**	**7.9**
- production costs	**10.3**	**11.9**	**18.7**	**13.2**
- sum	**21.6**	**15.4**	**25.5**	**25.1**
Total	***-3.8***	***-4.5 – 4.0***	***-2.4 – -0.6***	***-9.4 – -1.5***

The biogas production compensates for the lower pulp price; hence the process seems to have potential for further investigation. The advantage of the "chemical" approach is the clearly higher pulp yield, which increases the income from the pulp. However, at the current stage, the process consumes high amounts of chemicals, which significantly increases the production costs and environmental impact.

Possibilities for Combined Straw Pulp and Energy Production

In Europe, the possibilities for combined straw pulp and energy production seem to be limited, unless the price of recycled paper increases above 200 Eur/Adt or significant subsidies are made to encourage bioenergy production. Then the mills which would most benefit from the cheaper raw material are the small containerboard mills with a risk of dropping out when the demand decreases. These mills typically utilise recycled fibres.

The locations of containerboard mills based on the use of recycled fibres in Europe are presented in Fig. 2. Several small-scale containerboard mills are located in France. These mills could benefit from the straw pulp use if the price was profitable. In addition, the area of agricultural land in France is over half of the land area. Hence a potentially favorable option for a combined straw and energy production in Europe could be in France.

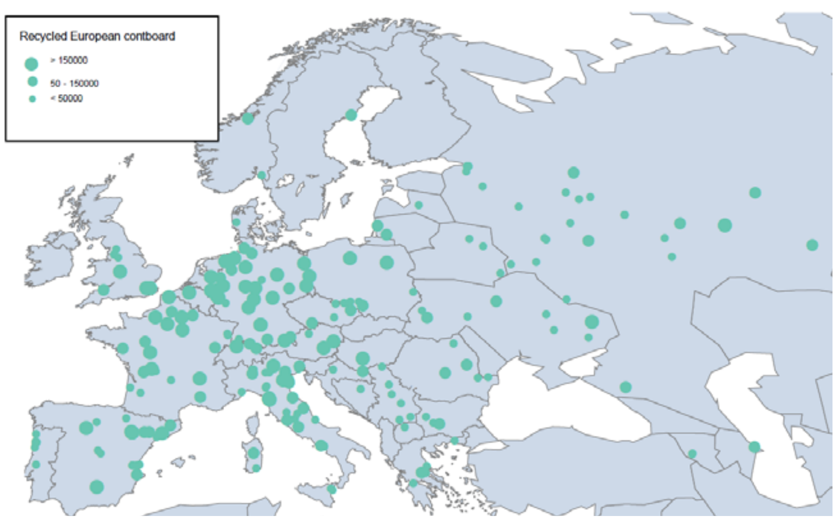

Fig. 2. Recycled fibre-based containerboard mills in Europe (Pöyry 2010).

In China, the chronic shortage of fibres enables the utilisation of straw as a raw material for papermaking. As the demand for fibres and renewable energy produced in an environmentally safe way is a priority in China, this fact could open possibilities to suggested combined straw pulp and energy production in a small scale if the price were acceptable.

CONCLUSIONS

1. Adequate quality pulp for fluting production can be produced by hot water treatment and mechanical refining at a high temperature. The lower quality material, such as dissolved solids and fines, could directly be utilised for biogas or bioethanol production.
2. Due to the simple process, investment costs are moderate and chemical recovery is not needed. However, the process is economically competitive only if the price of produced pulp and biogas would be significantly higher than the current price of recycled fibres and natural gas. This indicates that subsidies may be required to promote this environmentally safe process to the markets.
3. A similar kind of hydrothermal pretreatment is needed prior to bioenergy and fibres production.
4. In Europe, suitable locations for small combined pulp and energy units are suggested to be in France. In China, they could replace environmentally acceptable smallish units without recovery or integrated with containerboard production.
5. Further research is needed to optimise the mechanical pulp production from straw by a hot water treatment and subsequent mechanical refining at a high temperature.

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Article submitted: November 2, 2011; Peer review completed: December 11, 2011; Revised version received: January 12, 2011; Accepted: February 16, 2011; Published: February 18, 2011.