The Use of Reed Canary-Grass (*Phalaris arundinacea*) as a Short Fibre Raw Material for the Pulp and Paper Industry

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Doctoral Thesis

Swedish University of Agricultural Sciences

Umeå 2003

Acta Universitatis Agriculturae Sueciae
Agraria 424

ISSN 1401-6249
ISBN 91-576-6458-7

Printed by: Grafiska Enheten, SLU, Umeå, Sweden, 2003

Abstract

Finell, M., 2003. *The use of reed canary-grass (Phalaris arundinacea) as a short fibre raw material for the pulp and paper industry*. Doctoral dissertation.
ISBN 91-576-6458-7, ISSN 1401-6249

This thesis describes the use of delayed harvested reed canary-grass (*Phalaris arundinacea*) as a short fibre raw material for the pulp and paper industry. This study examines the following aspects of reed canary-grass: quality, transportation, storage, refining of the raw material by dry fractionation, chemical pulping, bleaching and paper production.

The delayed harvesting method of reed canary-grass produces an economically and environmentally sustainable short fibre raw material for the pulp and paper industry. The ash content and fibre properties of reed canary-grass depend on soil type and growing location. The yearly variation in fibre yield and fibre properties is also considerable. There is, however, a potential for minimising quality variations by choosing reed canary-grass varieties suitable to a specific growing location. The leaf and leaf sheath content of reed canary-grass also affects the quality of the pulp. These quality variations can be eliminated by dry fractionation, a method that removes the unwanted parts of the grass. These unwanted parts can be used as a valuable bio-fuel raw material. Transport of reed canary grass after fractionation can be improved by briquetting, a method that doubles the transport capacity of reed canary-grass compared to that of birch logs on a fibre basis. High quality short fibre chemical pulp can be produced from reed canary-grass. The whole process from grass production to pulp production has been demonstrated successfully in full scale. Bleached reed canary-grass pulp can be used in products such as fine paper and white-top liner paper.

Keywords: Non-wood, pulp properties, raw material preparation, TCF bleaching, paper properties, multivariate data analysis, PLS.

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The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.

Sir William Bragg

Contents

Appendix

List of original papers

This thesis is based on the following papers, which are referred to in the text by their respective Roman numerals.

I. Finell, M. and Nilsson, C., 2003. Variations in ash content, pulp yield, and fibre properties of reed canary-grass. Submitted.

II. Finell, M., Nilsson, C., Olsson, R., Agnemo, R. and Svensson, S., 2002. Briquetting of fractionated reed canary-grass for pulp production. *Industrial Crops and Products 16* (2002) 185-192.

III. Finell, M. and Nilsson, C., 2003. Kraft and soda-AQ pulping of dry fractionated reed canary-grass. In press. *Industrial Crops and Products*.

IV. Finell, M., Rehnberg, O. and Nilsson, C., 2003. Bleached reed canary-grass pulp used to produce white top liner. Submitted.

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Background

Today the Nordic pulp and paper industry imports a large part of their short fibre raw material, mainly birch, from Russia or the Baltic countries. The world consumption of paper, especially fine paper, is expected to increase, which indicates an increased demand for short fibre material. The Nordic forests are unable to satisfy the demands for short fibre raw material. At the same time, Sweden and the rest of Europe struggles with overproduction of food, which has led to large fallow agricultural areas (Paavilainen & Torgilsson, 1994). In the Nordic countries, especially the northern parts, extensive farmlands have been abandoned over the last 40 years.

Delayed harvested reed canary-grass (RCG) has shown is the most suitable crop for short-fibre production under Nordic conditions. Delayed harvested RCG is superior to summer or autumn harvested RCG because of lower production costs, better storage properties, lower mineral content (with the exception of silica), and better fibre properties. The delayed harvested dry material further shows a potential for refinement by dry fractionation, a method that removes undesirable parts of the grass.

Reed canary-grass fibres can replace birch fibres in certain paper grades. When using RCG as a short-fibre raw material, some aspects and limitations must be taken into consideration:

- The size of the pulp mill is important. Chemical pulping requires large and expensive units to obtain profitability. A profitable size in Nordic conditions is about 400,000 tons of pulp per year.
- To guarantee year around availability of raw material, the raw material must be dry enough to store for extended periods. Storage requires some kind of compression of the raw material to decrease transport and storage costs.
- The raw material should be refined/fractionated before pulping. This can be done either at the pulp mill or in a separate pre-treatment unit.
- RCG needs special equipment for pulping. A conventional fibre line for wood-based raw materials can not handle RCG. The cooking conditions for RCG is also quite different from those of wood.
- RCG contains much more silica than wood-based raw materials. This causes problem in the chemical recovery line. Equipment for silica removal from the spent cooking liquor is necessary.
- Production of RCG should be independent of agricultural subsidies to guarantee an economically sustainable raw material base for the pulp and paper industry.

Because of the above considerations, RCG should use the delayed harvested method, dry fractionation, and a separate fibre line in pulp mills producing both hardwood and softwood pulp. The economic benefits of a large-scale pulp mill will result even if the RCG line only contributes a small part of the pulp production. Bleaching of RCG pulp can be done together with oxygen delignified birch pulp. After silica removal, the spent cooking from RCG cooking can be recovered together with the spent liquor from the other fibre lines. A RCG line with the capacity of 100,000 tons of pulp per year would require about 40,000 ha of RCG (Paavilainen, Tulppala & Balac, 1996).

This thesis concentrates on some of the problems and opportunities associated with the use of non-woods and especially delayed harvested reed canary-grass for pulp and paper production. Dry fractionation of the raw material is a central process in all four papers included in this work. Paper **I** shows the variations in ash content, pulp yield, and fibre properties of fractionated reed canary-grass. Hand fractionated RCG was used in this trial, and the fibre properties of thirteen RCG varieties grown at eleven different locations were studied. Paper **II** investigates the effect briquetting has on pulp properties. This paper shows the potential for improving transport and storage of the dry fractionated raw material. Paper **III** shows the effect of dry fractionation, alkali charge and cooking time on pulp yield and fibre properties for the kraft and soda-AQ processes. The importance of properly fractionated raw material is shown in this study. Paper **IV** investigates the use of bleached reed canary-grass pulp in white-top liner paper. Dry fractionated and briquetted reed canary-grass was used as raw material for the pulp produced in a mill-scale trial.

Introduction

Over the last 15 years, research projects on agriculturally produced raw materials for fibre production have been launched in both Sweden and Finland. After Sweden and Finland joined the EU, a larger project that included six northern EU countries was started. This section gives some information on the present use and potential use for European non-wood material and summarises the findings from three agro-fibre projects.

Non-wood use in Europe

The production of non-wood pulp (based on straw and new industrial crops) will double by 2010 in Eastern European countries from the current level of less than 400,000 tons per year. In Western Europe, current levels of non-wood pulp production are expected to increase by 300% by 2010. It is also predicted that small-scale non-wood pulp production, about 30,000 tons per year, will be underway in the Nordic countries by 2010.

In Europe, non-wood pulp capacity is based mainly on cereal straw. Industrial crops are the second most important raw material source in the European non-wood pulp industry, especially in the form of cotton linters. Political, economic, and environmental issues favour growing special plants. More advanced use techniques and logistics for reed canary-grass, miscanthus, sorghum, kenaf, and hemp are also being developed in Europe (Paavilainen, 1998a)

The capacity of most non-wood mills in Europe is less than 5,000 tons per year, but there have also been a few larger-scale operations in Europe. The largest western European mill was owned by Saica and was located in Zaragoza, Spain. The mill produced mainly testliner and fluting (for corrugated fibreboard) and the annual straw pulp capacity was 120,000 tons. The largest eastern European mill was located at Dunaujvaros in Hungary. It produced 30,000 tons per year of un-coated wood-free papers from straw. Both Saica and Dunaujvaros, however, closed recently because they could not comply with tightening environmental regulations. This indicates that the above-mentioned forecast by Paavilainen (1998a) is somewhat optimistic.
(http://www.fiberfutures.org/straw/main_pages/07_markets/2_pulp_paper.html; 17-Sept-2003).

The Swedish agro-fibre project 1987-1991

The background of the project (Project Agro-Fibre) was that large areas of land were to be withdrawn from food production. At the same time, the pulp and paper industry was importing large quantities of hardwood for short fibre production. The project had several goals:

to decide if it is possible to produce good quality chemical pulp from any of about 20 different crops;

to decide if a modern alkaline process can be used without problems with chemical recovery and pollution; and

to decide if it is possible to produce the pulp at prices that are competitive with wood based pulps.

Fibre properties of 20 different crops were studied and four crops were selected for more detailed studies. These crops were Alfalfa (*Medicago* spp.), Common Melilot (*Melilotus officinalis*), Reed canary-grass (*Phalaris arundinacea*), and Elephant grass (*Miscanthus x giganteus*). The fibre properties of these four species were acceptable for production of high quality paper. Table 1 shows some properties of the grass pulps compared to birch pulp.

Table 1. *Judgement of the effects of replacing birch kraft pulp with non-wood kraft pulp in printing paper.*

Crop	Drainage	Surface	Strength	Stiffness	Light scattering
Alfalfa	Poorer	Better	Same	Same	Poorer
Melilot	Poorer	Better	Same	Same	Same
Reed canary-grass	Poorer	Better	Same	Same	Poorer
Elephant grass	Same	Same	Same	Better	Poorer

Up to 30% of the hardwood fibres in printing paper and cartons could be replaced without adverse effects. This investigation concludes that the best non-wood material is elephant grass, a material that has similar fibre properties as hardwood. The other materials have fibre properties similar to straw pulp.

Two production systems were studied. Harvest of fresh grass in the summer with storage in large silos similar to forage production, and harvest of grass in the autumn with field drying and baling.

Of the alkaline pulping processes investigated in this project (kraft, soda, soda-AQ and NACO, which is a process based on oxygen delignification and Na_2CO_3 in a special pulper), the kraft process was found to be most efficient.

The economic evaluation showed that the raw material cost was reasonable, but the capital cost for a pulp plant producing 100,000 tons of pulp per year was too high. It was not possible to build a pulp plant with an output greater than 100,000 tons of pulp per year based on agricultural crops. This was due to logistic problems and de-watering problems in the process limiting the production. The critical point in the mill was the recovery plant because this part of the plant would be too expensive for a pulp mill of the above-mentioned size (Berggren, 1991).

The Finnish agro-fibre project 1993-1995

The reasons for launching this project (production and use of agrofibre in Finland) were the same as for the above-mentioned Swedish project. The goal of the project was to find out if it was technically and economically possible to replace some of the imported wood-based short fibre raw material (birch) with domestic produced agro-fibre. The first part of the project investigated different grasses and harvesting methods suitable for fibre production. Among the grasses, reed canary-grass (*Phalaris arundinacea*), tall fescue (*Festuca arundinacea*), meadow fescue (*Festuca pratensis*), cocksfoot (*Phleum pratense*), and brome grass (*Bromus inermis*), reed canary-grass was found to be the best suited for short fibre production when using the delayed harvesting method for bio-fuel production suggested by Olsson *et al*. (1989) (Pahkala *et al*., 1996).

The second part of the investigation focused on the suitability of traditional, long established methods already widely used in agriculture applied on the spring harvest (delayed harvest) of grasses and on the development of mechanical pre-treatment of the grass (air separation). Production costs for reed canary-grass from establishment to transport to the pulp mill was also studied. The investigation showed that good-quality short fibre raw material could be produced from delayed harvested RCG if the leaves were removed before pulping. Simple, covered, outdoor stacks were found to be a practical, low-cost storage alternative. The production costs of RCG were found competitive with fodder barley (Hemming *et al*., 1996).

The third part of the project concentrated on alternative processes for delignification of grasses. Fungi and enzyme treatment before cooking and cooking methods based on trisodium phosphate, formic acid + hydrogen peroxide (Milox) and ethanol (IDE) were studied. The results showed that pre-treatment of RCG with fungus significantly reduced the fines content of RCG pulp and improved the paper properties. The alternative pulping processes produced a pulp with almost similar quality as conventional processes, and the alternative processes had potential to handle the high silica content of the grasses. These methods are, however, not yet in commercial use (Laamanen & Sundquist, 1996).

In the fourth part of the project, kraft cooking, bleaching, and papermaking of RCG was studied. It was found that delayed harvested RCG was easy to cook to low kappa levels. RCG pulp could be bleached to full brightness using both ECF (Elemental Chlorine Free) and TCF (Totally Chlorine Free) bleaching sequences. Silica dissolved in the spent liquor could be removed with commercial techniques by precipitation with flue gasses or by two-stage causticising. The RCG pulp gave good printing properties in fine paper, but the strength properties were somewhat lower compared to average birch pulp. The differences in the measured properties were, however, within the limits of the property variations of mill birch pulp. The de-watering ability of RCG pulp was, however, inferior to that of birch pulp, but laboratory simulation tests showed that there were no differences in sheet dryness before or after pressing irrespective of whether birch or RCG was used as the short fibre pulp in the papermaking stock.

The results of the laboratory trials were confirmed in pilot-scale trials by making coated and surface-sized fine paper and by testing the printability of the paper in offset printing. The trials indicated that RCG pulp could be used in coated or surface-sized fine paper without adversely affecting the runnability or the quality of the paper. Table 2 shows a summary of the RCG-based fine paper properties found as compared to those of birch-based fine paper (Paavilainen & Tulppala, 1996).

Table 2. *The suitability of delayed harvested reed canary-grass for fine paper (Paavilainen & Tulppala., 1996)*

		Reed canary-grass	Birch
Runnability	Tensile strength	0	0
	TEA	+	0
	Tear strength	-	0
	Drainage	(-)	0
Printability	Opacity/light scattering	0(+)	0
	Bulk/conformability	0	0
	Smoothness	(+)	0
	Porosity	0	0
	Surface strength	+	0
	Stiffness	0	0
	Dimension stability	(-)	0

It was found that integrating a RCG fibre line into a pulp mill producing both hardwood (birch) pulp and softwood (pine/spruce) pulp was the most promising concept for Finnish conditions. Economic calculations for a pulp mill producing 100,000 tons of RCG pulp per year, 150,000 tons birch pulp per year, and 250,000 tons of softwood pulp per year were compared to a reference mill that produced 250,000 tons of birch pulp per year and 250,000 tons of softwood pulp per year. This study showed that they had equal profitability (Paavilainen *et al*., 1996a).

The EU reed canary-grass project 1995-1999

The background to this project was the need to find economic and an environmentally friendly use of set aside land in the EU countries. Multifunctional use of grasses as bio-fuel and papermaking pulp was considered a promising option in which crops also would be needed in bulk quantities. The goal of this project, AIR3-CT94-2465, was to develop reed canary-grass as an economically and environmentally competitive industrial crop for combined production of high quality chemical pulp and bio-energy fuel powder. The chemical pulp part of the project was based on the positive results from the above mentioned Finnish agro-fibre project. The project was divided into 5 main objectives:

- Evaluation of how RCG plant-breeding materials from different European countries function as industrial crops. Quality and homogeneity studies of RCG and development of the delayed harvesting system for use in larger areas of Europe.
- Developing the intermediate processing technique for optimising the quality of pulp as well as bio-fuel quality.
- Evaluating how the bio-fuel fraction can be an economically and environmentally sound way to replace oil.
- Evaluating chemical pulping processes for reed canary grass.
- Making economic and feasibility studies of the whole chain from crop production to pulp, paper, and energy production.

The results from the first part of the project showed that the new breeding lines of reed canary-grass had a large potential for getting higher yields and better quality than the existing varieties. The best breeding lines tested gave on average a yield of 20% higher (9.6 tons/ha) than now existing forage varieties (8.0 tons/ha), but yields up to 16 tons/ha at certain locations were also reported when using the delayed harvest method. The breeding lines used in this project were not suitable for crop production in maritime climates. The yields were lowest in the most southern located trials mainly depending on dry conditions during the growing season and a large decrease of biomass during winter depending on loss of leaves during winter in snow free areas (Olsson & Landström, 2000; Olsson *et al*., 2001).

The quality and homogeneity studies showed that delayed harvest gave important quality benefits for both fuel and papermaking pulp end uses and that the quality was strongly influenced by soil conditions and growing locations (Paper **I**). The quality evaluation method development with NIR (near infrared reflectance) spectroscopy produced good results concerning possibilities to quantify the proportion of internodes (pulp raw material) and leaves, leaf sheaths, and nodes (bio-fuel raw material) of the harvested crop (Magnusson, 1997; Nilsson *et al*., 1998).

The intermediate processing studies were focused on developing a low energy input and cost effective dry fractionation process, based on disc milling technology. Before cooking, RCG should be fractionated using disc mill fractionation. Fractionation improves the papermaking properties of the pulp and increases the pulp yield. This mechanical pre-treatment reduces the amount of silica by 30-40% entering the process and improves the bleachability of RCG pulp. (Paavilainen, Tulppala & Balac, 1996; Finell, Hedman & Nilsson, 2000; Paper **III**). To improve storage and transport logistics and economy, fractionated RCG was suggested to be baled in high-density bales or preferably briquetted (Paper **II**; Finell, Burvall & Olsson, 1998). The intermediate processing was also found to produce a good raw material for upgrading to powder fuels, briquettes, and pellets.

The reed canary-grass bio-fuel pellets from the leaf fraction had high ash content; therefore, specially designed boilers that can handle large amounts of ash must be used (Paulrud & Nilsson, 2001). Because combustion process produced a large amount of ash, there was difficulty burning reed canary-grass pellets in equipment designed for wood pellet combustion. RCG was easier to burn in the form of briquettes.

The chemical pulping part of the project concentrated on two processes, the kraft process and the soda-oxygen process. The dry fractionated RCG produced pulp yields of about 54% in kraft cooking (Paper **III**) and up to 58% in soda-oxygen cooking at kappa level 10. The pulp yield of birch is about 51% at kappa level 20. RCG kraft and soda oxygen pulps could be bleached to full brightness of 90% ISO with a short ECF sequence using the same chemical charge as with oxygen-delignified birch pulp (Olsson *et al*., 2001). With a TCF sequence, the final brightness of kraft RCG pulp was in the same study found to be 88% ISO, but the final brightness of soda-oxygen RCG pulp only reached 85% ISO.

The dissolved silica in the spent liquor could be removed from the recovery cycle by precipitating it from weak black liquor with flue gases or by two-stage causticising. In soda-oxygen cooking, the main portion of silica precipitated onto the fibres. This makes it possible to run the soda-oxygen mill with only minor problems caused by silicon compounds (Paavilainen, Tulppala & Balac, 1996).

Using delayed harvesting, dry fractionation, and briquetted RCG was tested in full scale at the AssiDomän Karlsborg mill in a Tampella-type sawdust digester. The desired pulp quality was reached very soon after the sawdust remaining in the feeding line had passed the digester. The digester itself was found suitable to cook RCG, but clogging of the feeding screws showed that continuous operation of such a digester using RCG requires some modifications of the feeding equipment. The mill-cooked RCG pulp had excellent quality (especially its optical properties), and was suitable as the short fibre component in white-top liner paper (Paavilainen *et al*., 1999; Paper **IV**).

The process concepts evaluated, were, the integration of a RCG line (100,000 tons RCG pulp per year) into a Nordic mill cooking wood (150,000 tons of hardwood pulp per year and 250,000 tons of softwood pulp per year); and a Central European mill using the soda-oxygen cooking process with a capacity of 300,000 tons of RCG pulp per year (Olsson *et al*., 2001).

The profitability of the RCG mills and wood mills was almost at the same level but slightly in favour of the RCG mills. The economic calculations and the good quality of the RCG pulp tested indicates that Central European soda-oxygen and Nordic integrated kraft RCG mills would be serious competitors to corresponding hardwood and hardwood/softwood reference kraft pulp mills (Olsson *et al*., 2001).

A number of calculations and logistic systems were presented for different RCG production systems. Finland and Sweden possess the best conditions for a viable production of RCG as a short fibre raw material for the pulp and paper industry. Under certain circumstances, RCG pellets were a competitive fuel in Sweden and Finland (Pedersen, 1998; Olsson *et al*., 2001).

Environmental considerations

A Life cycle assessment (LCA) was made to compare a typical integrated fine paper mill producing 50% pine and 50% birch pulp with a similar mill where 40% of the birch is replaced with RCG. The results showed that the most considerable difference between the mills was the waste production. The RCG mill produced more lime sludge because of the high silica content of RCG. In all other categories, the difference between the mills was small and it was not possible to declare one mill better than the other from an environmental point of view (Hedenberg *et al.*, 1997).

Non-wood fibres for papermaking

Non-wood fibres are an important raw material source for papermaking in many developing countries. Of the world's total pulp production, non-wood pulp represents close to 10%. In developing countries, however, non-wood pulp production is often much higher, especially in China and India where non-wood pulp production is about 70%. This section will give some background information on the present use of non-wood fibres world-wide.

Non-wood fibres can be divided according to their origin: agricultural by-products (straw, bagasse, etc.); industrial crops (cotton linters, hemp, etc.); and naturally growing plants (bamboo, reeds, etc.). Agricultural by-products are characterised by a low raw material price and moderate quality. High quality pulp can be produced from industrial crops, but the raw material is more expensive; however, the raw material costs of natural plants are competitive with wood. One of the main problems for the moment is limited availability, which restricts widespread use of such raw materials in papermaking.

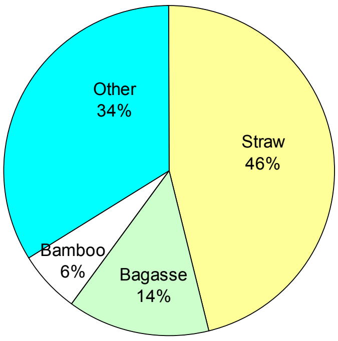

Figure 1. Worldwide use of different non-wood raw materials for pulp production. Data from Paavilainen (1998a).

Table 3. *Average fibre length of some non-wood plant fibre pulps (Data from Atchison, 1998)*

Raw material	Average fibre length (mm)
Abaca (Manila hemp)	6.0
Bagasse (well depithed)	1.0 - 1.5
Bamboo	1.7 - 4.0
Corn stalk (well depithed)	1.0 - 1.5
Cotton fibre	20 - 25
Cotton linters	1.0 - 2.0
Cotton stalks	0.6 - 0.8
Crotalaria (Sunn hemp) bast fibres	2.5 - 3.5
Esparto grass	1.5
Flax tow from seed flax straw	25 - 30
Hemp bast fibre	20
Jute bast fibre	2.5
Kenaf bast fibre	2.6
Kenaf core material	0.6
Ramine	200
Reeds	1.5 - 2.5
Rice straw	0.8 - 1.0
Sisal	3.0 - 3.5
Wheat straw	1.0 - 1.5
For comparison purposes	
Temperate zone coniferous wood (softwood)	2.7 - 5.0
Temperate zone hardwoods	0.8 - 1.7
Mixed tropical hardwoods	0.7 - 3.0
Eucalyptus	0.8 - 1.3
Gmeline	0.8 - 1.3

The most common non-wood sources for pulp production are straw, bagasse, and bamboo. In addition, other materials such as jute, kenaf, hemp, flax, reeds, and other grasses are used. Agricultural by-products account for 73% of the world’s non-wood pulp capacity, natural plants such as reed and bamboo account for 18%, and the remainder consists mainly of industrial crops (Paavilainen, 1998a). Figure 1 shows the world-wide use of different non-wood raw materials for pulp production.

Non-wood raw materials can be classified according to fibre length. In broad terms, this means long fibres can be used instead of softwood sources in different end-products, and short fibres can be used instead of hardwood sources in different end products. Some plants (such as hemp, kenaf, and jute) contain both types of fibre. By separating the bast fibres and core fibres, it is possible to produce a high quality long fibre and a lower quality short fibre from these plants (Paavilainen, 1998a). Table 3 shows the average fibre length of pulp from some non-wood materials compared to the fibre length of wood materials.

Advantages and disadvantages of non-wood fibres

Throughout the cycle, from cultivation to use, fibres derived from non-wood plants differ from those derived from wood.

Advantages

Many non-wood fibres are derived from annual plants. The advantage of annual plants is that they can be grown on farmland and harvested each year with high yields (5-20 ton/ha). Table 4 shows some typical annual yields of some various papermaking raw materials.

Table 4. *Annual yields of various papermaking raw materials (Paavilainen & Torgilsson, 1994).*

Plant	Fibre annual yield t/ha	Pulp annual yield t/ha
Scandinavian softwood	1.5	0.7
Fast growing softwood	8.6	4.0
Temperate hardwood	3.4	1.7
Fast growing hardwood	15	7.4
Wheat straw	4.0	1.9
Rice straw	3.0	1.2
Bagasse	9.0	4.2
Bamboo	4.0	1.6
Kenaf	15	6.5
Hemp	15	6.7
Elephant grass	12	5.7
Reed canary-grass	8	4.0

Table 4 shows that RCG produces twice as much pulp annually compared to temperate hardwood (birch). In Sweden and Finland up to the Arctic Circle (66.5 °N), growing RCG has provided good yields using the delayed harvesting method. The yield of delayed harvested RCG is independent of latitude. New breeding lines have also shown potential for significant yield improvement for this crop (Olsson & Landström, 2000; Sahramaa & Jauhiainen, 2003). For the Nordic countries, rice straw, bagasse, bamboo, and kenaf are not suitable for climatic reasons. Elephant grass is limited to the southernmost parts of Sweden (Berggren, 1991). Cereal straw is, however, a potential short fibre source. The disadvantage of cereal straw is that it is a by-product from food/feed production and not harvested at optimal conditions for fibre production, thereby giving a lower pulp yield compared to RCG. Cereal straw is also highly dependent on agricultural subsidies thus making long-term availability unreliable, especially in the Nordic countries. Hemp is a highly interesting industrial crop for central Europe and recently also for the Nordic countries (Nilsson, 2003).

Chemical pulping processes for wood are designed principally to eliminate lignin with minimum damage to the papermaking properties of the cellulose fibres. As can be seen from Table 5, the majority of non-wood fibrous raw materials have considerably less lignin than the wood-based materials. This means that most non-wood materials can be pulped with simple chemical systems such as caustic soda. The alkali charge required for a non-wood fibrous raw material is normally lower than what is required for a wood based raw materials to achieve the same degree of delignification.

Table 5. *Chemical properties of some non-wood and wood materials (Kocurek & Stevens, 1983)*

Plant material	Alpha cellulose (%)	Lignin (%)	Pentosans (%)	Ash (%)	Silica (%)
Rice	28-36	12-16	23-28	15-20	9-14
Wheat	29-35	16-21	26-32	4.5-9	3-7
Barley	31-34	14-15	24-29	5-7	3-6
Oat	31-37	16-19	27-38	6-8	4-6.5
Rye	33-35	16-19	27-30	2-5	0.5-4
Sugar cane	32-44	19-24	27-32	1.5-5	0.7-3.5
Bamboo	26-43	21-31	15-26	1.7-4.8	0.7
Esparto	33-38	17-19	27-32	6-8	-
Sabai	-	22	24	6	-
Reed	45	23	20	2.9	2
Seed flax tow	45-68	10-14	6-17	2.3-4.7	-
Seed flax	34	23	25	5	-
Kenaf	-	15-19	22-23	1.7-5	-
Jute	-	21-26	18-21	0.5-1.8	-
Abaca	61	9	17	1.1	-
Sisal	43-56	8-9	21-24	0.6-1.1	-
Cotton linters	80-85	-	-	0.8-1.8	-
Softwood	40-45	26-34	7-14	<1	-
Hardwood	38-49	23-30	19-26	<1	-

The use of non-wood materials can reduce deforestation in some countries and reduce emissions of carbon monoxide and carbon dioxide that arise from the burning of waste agricultural residues (Moore, 1996). Another advantage of using non-wood materials for pulp production is that it can have a positive effect on employment and social structure in sparsely populated areas.

Disadvantages

The logistics needed for annual plants are a major problem for the introduction of non-wood based fibres into the paper industry. Large stocks and adequate storage at constant quality by drying or ensilage may be necessary to service large-scale operations. Alternatively, where non-wood pulp mills are based on agricultural residues or annual crops that are grown in scattered locations, they need to be kept small to minimise transport costs of raw materials. On a fibre-basis, straw bales take about three times as much space as logs (two times as much for RCG, Paper **II**), so transport is two to tree times as expensive. This considerably limits the supply radius for a straw-based pulp mill. Briquetting RCG before pulping, as described in Paper **II**, shows a potential method for increasing the supply radius because twice as much RCG material can be transported compared to birch logs. In addition, the bales are bulky and are more difficult to handle than wood chips. Small size mills cannot, however, benefit from the economics of scale enjoyed by more transport-efficient wood-based mills.

Non-wood fibrous materials normally have higher ash and silica contents (Table 5). Most of the silica dissolves during alkaline cooking and remains as an undesirable constituent of the spent liquor. The problem with cereal straw is that its high silica content causes many problems (such as scaling) in the chemical recovery process which reduces the efficiency of some equipment and actually can plug it and increase viscosity, making it difficult or impossible to pump the black liquor to some parts of the recovery process. These problems make chemical recovery difficult, less efficient, and more costly as compared to recovery of black liquor from wood (Moore, 1996).

Another property very different from hardwood fibre is that the water retention (de-watering or drainage) capacity of straw fibre is much higher than of hardwood fibre. Table 6 shows the fibre length and drainage resistance for unbeaten pulp for some non-wood materials compared to birch pulp. It can be seen that all non-wood materials have a higher drainage resistance (°SR) than birch pulp. The difference within the same species (RCG) can also be considerable. This is probably a result of different harvest times and pre-treatment methods. The water retention is a significant aspect because a large part of making pulp is separating fibre and water and the production capacity will be lower for straw and many other non-wood materials compared to hardwood.

Table 6. *Fibre length and drainage resistance for kraft pulp from some non-wood raw materials compared to birch kraft pulp (Thykesson, Sjöberg & Ahlgren, 1997)*

Raw material	Pulp yield (%)	Kappa no.	Fibre length (mm)	Drainage (°SR)
Birch	52.2	19.3	0.9	12
Wheat straw	58.7	48.8	1.0	28
Elephant grass	55.4	36.3	1.1	21
Reed canary-grass	37.7	36.7	0.8	65
Reed canary-grass*	52.7	12.5	0.9	26

* Data from Paper **I**

Variation in raw material homogeneity is a factor that must be taken into account when using non-wood pulping raw materials. To a great extent, straw and RCG fibre is characterised by variations in plant size and composition due to variations in cultivation conditions, climate, soil, etc. (Paper **I**), variations in storage time

(from a few days old to a few years old at the pulp mill), and variations in the rate of deterioration during storage. This variation needs strict quality control, and means a supplier has a higher risk that bales will be rejected than in case of a wood fibre supply; however, with proper quality control, this variation can be managed.
(http://www.fiberfutures.org/straw/main_pages/07_markets/2_pulp_paper.html; 17-Sept-2003).

Reed canary-grass

Reed canary-grass (RCG) (*Phalaris arundinacea*) is a perennial robust coarse grass about 2 m high that is widely distributed across temperate regions of Europe, Asia, and North America. The plant frequently grows in wet places, along the margins of rivers, streams, lakes, and pools. RCG can be grown on most soil types but gives the best result on light organic-rich soil types. RCG spreads naturally by creeping rhizomes, but plants can be raised from seed. Yields of 8-10 tons per ha of dry matter are obtained when harvested in summer and yields of 6-8 tons per ha are obtained when the delayed harvest method is used. RCG is a very sustainable crop and the productivity is tending to increase in successive years with careful management. RCG is assumed to give a high yield for at least 10-15 years when the delayed harvest method is used (Landström & Wik, 1997).

In Sweden and Finland, RCG is a suitable crop for short fibre pulp production. RCG gives a high yield of fibres per hectare (Wisur, Sjöberg & Ahlgren, 1993) and is also the most suitable plant for the delayed harvesting method in the Nordic climate (Saijonkari-Pahkala, 2001).

Delayed harvest

The delayed harvest system for RCG was developed at the Swedish University of Agricultural Sciences in Umeå in the mid-1980s. The aim of the method was to delay the harvest to a period when dry biomass could be harvested in the field. For northern Sweden, where the fields in wintertime are covered with snow, the harvest (once a year) is delayed until early spring when the snow has melted and just before the new growth starts. Translocation of nutrients from the leaves and stem to the root system will occur during autumn and winter, which enables good quality for bio-fuel and fibre and lowers the need of fertilisation. The crop is left in the field during the winter and harvested as wilted material the following spring when the soil is dry enough to make harvest possible. It is then possible to harvest under favourable weather conditions and to obtain storable dry material directly from the field, which reduces production costs (Landström, Lomakka & Andersson, 1996; Landström & Olsson, 1998).

The delayed harvest is beneficial for both bio-energy and fibre production from RCG. Storage and transport are similar for both end uses, but for bio-energy the loss of chlorine, sulphur, and alkali has a very positive effect on the ash fusion temperature (Burvall, 1997). For fibre production, the delayed harvest gives higher pulp yield, less variation, and stronger fibres. Dry matter loss during winter does not include fibrous cellulosic matter, thus the pulp yield will increase (Paavilainen & Torgilsson, 1994; Olsson, Torgilsson & Burvall, 1994; Finell, Olsson & Backlund, 2002).

Chemical composition

Delayed harvested RCG can be divided into four main components: leaves, leaf sheaths, nodes, and internodes. The internodes of the stem are the most suitable part of the plant for pulp production because the leaves and leaf sheaths contain less fibrous material and more ash than the internodes (Pahkala & Pihala, 2000). Figure 2 shows the main components of RCG and Table 7 shows the ash and mineral composition of the different plant parts. Table 8 shows the nutrient and ash content of RCG divided into two fractions (leaf and stem) for delayed and autumn harvested RCG.

Interestingly, the data presented by Pahkala & Pihala (2000) in Table 7 shows that the ash and silica content increases in the plant when the delayed harvest method is used. The data presented by Landström, Lomakka & Andersson (1996) in Table 8 indicates that the ash and silica content will be lower when using the delayed harvest method. Both sources, however, clearly indicate that the potassium content of the grass is lower in the delayed harvested material. Mortensen (1998) reports that delayed harvest of RCG decreases potassium and chloride with more than 80% and ash and silica with 50%. This agrees with results presented by Landström, Lomakka & Andersson (1996). Burvall (1997) reported a slight decrease (12.5%) in ash content but an increase (54%) in the silicon content of delayed harvested RCG; however, chlorine and potassium was clearly lowered (80%) in delayed harvested material.

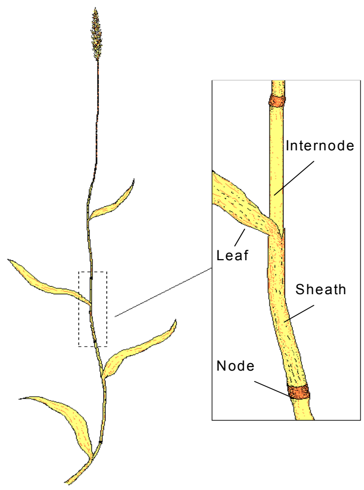

Figure 2. The RCG stem is divided into segments (internodes) by nodes. Every leaf is attached to a sheath, which surrounds the stem from the bottom of the leaf down to the node (Magnusson, 1997).

The low concentration of nutrients in the delayed harvested RCG means lower demand for fertilisation, which implies lower production costs than required by a summer harvest system. The low concentration of chlorine in the spring-harvested material is also very favourable when RCG is used as a bio-fuel because chlorine is an undesired element in combustion. The low potassium content is important for RCG combustion especially at low ash contents because a low potassium content improves (rises) the ash melting temperature (Paulrud, Nilsson & Öhman, 2001). The low contents of potassium and chlorine found after delayed harvest are due to leaching from the crop during the winter (Landström, Lomakka & Andersson, 1996).

Table 7. *The mean value for ash and mineral content of the plant components for delayed and autumn harvested RCG. One variety (Venture), grown at one location in Finland, percent of dry matter (Pahkala & Pihala, 2000).*

Plant component	(%)	Ash (%)	SiO_2 (%)	K (g/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)
Delayed harvest							
Stem	61.3	5.04	4.04	2.77	6.34	61.4	48.0
Leaf sheath	18.5	9.00	7.40	3.57	7.33	267	140
Leaf	20.1	13.0	10.7	4.30	8.22	491	214
Autumn harvest							
Stem	51.6	4.71	1.67	14.5	5.90	18.7	20.0
Leaf sheath	17.4	8.44	4.27	19.7	4.11	66.7	52.8
Leaf	28.2	11.6	5.73	21.1	5.99	110	80.5

Table 8. *Mean values of nutrient and ash composition in leaf and stem of delayed and autumn harvested RCG. One variety (Palaton), grown at 10 different locations in Sweden, percent of dry matter (Landström, Lomakka & Andersson, 1996)*

Plant component	N (%)	K (%)	P (%)	Ca (%)	Mg (%)	Cl (%)	Ash (%)
Delayed h.							
Stem	0.70	0.24	0.08	0.12	0.04	0.11	3.42
Leaf	1.86	0.36	0.20	0.35	0.10	0.10	6.60
Autumn h.							
Stem	0.62	0.90	0.11	0.10	0.06	0.52	4.21
Leaf	2.32	1.59	0.25	0.69	0.26	1.07	8.51

The organic part of RCG is composed of cellulose, hemicellulose, lignin, and extractives. The chemical composition of the organic part of RCG largely depends on the date of harvest when using traditional harvest methods (summer or autumn). Table 9 shows the changes in protein, cellulose, hemicelluloce, and lignin content of RCG harvested in June and July. The protein content of the plant decreases and the cellulose, hemicellulose, and lignin content increases according to the date of harvest.

When using the delayed harvest method, the grass is dead and the change in chemical composition has ceased. There will, however, still be differences in chemical composition between growing locations and RCG varieties (Stewart, Hall & Morrison, 1997). Table 10 shows the chemical composition of the internode part of delayed harvested RCG from different varieties and growing locations.

Table 9. *Chemical composition of reed canary-grass (variety unknown) at different harvest dates, summer harvest, whole plant measured as percent of dry matter (Theander, 1991).*

Date of harvest	Protein (N×6.25) (%)	Cellulose (%)	Hemicellulose + pectin (%)	Klason lignin (%)
10/6	20.3	28.6	20.8	7.4
19/6	14.8	31.1	23.2	10.6
27/6	14.6	32.3	22.0	10.9
11/7	10.5	34.2	23.5	14.6
28/7	9.0	34.8	23.4	18.0

Table 10. *Chemical composition of 42 samples of delayed harvested reed canary-grass of different varieties and from different location, percent of dry matter. Only internodes (Dahlberg, 1998)*

	Extract (%)	Klason lignin (%)	Rhamnose (%)	Arabinose (%)	Xylose (%)	Galactose (%)	Glucose (%)
Mean	1.85	21.7	0.04	1.79	13.3	0.70	41.2
Max	3.68	26.9	0.36	2.91	17.5	1.62	44.5
Min	0.41	16.3	0.00	0.88	5.51	0.36	22.5

Insect pests

In Sweden, RCG is still cultivated on a limited basis (less than 500 ha) (Eriksson, 2003), and only a few serious attacks of insects or diseases on the crop have been reported. In Northern Sweden, however, a severe infestation of the gall midge *Epicalamus phalaridis* occurred in one field of RCG. Larvae of the midge feed beneath leaf sheaths and the crop lodges in late summer. In the infested field, population densities of the midge were very high for three consecutive years. The crop was weakened and the occurrence of weeds increased. The dry matter yields declined markedly and were after three years of midge-attack about 50% of the average yield in the preceding years.

The fibre properties of midge-infested parts of the internodes were poor, but because the midge-damaged parts of the grass were very brittle when using the delayed harvest method, it was found that these parts probably would be sorted out in a fractionation process. Another problem is the occurrence of weeds in the harvested crop. To what extent such material will influence the fibre properties is still unknown.

So far, the outbreak of *E. phalaridis* is a local phenomenon. Only in Northern Sweden has the gall midge been found on cultivated RCG, and only in one field has the population density soared to an outbreak level. Because *E. phalaridis* has been found on several RCG stands in natural vegetation, a further spread to cultivated crops can be anticipated if the cultivated area increases. The deterioration of the RCG stand in the field in Northern Sweden, however, indicates that *E. phalaridis* has potential to become a serious pest of RCG (Hellqvist, Finell, & Landström, 2003).

Variations in fibre properties

Variation in pulp yield and fibre properties of RCG largely depends on the harvest time, the pulping process, and the fractionation of the raw material before pulping. Other factors that might influence the properties of RCG pulp are the soil conditions at the growing location and the RCG variety used.

The effect of soil type on nutrient and ash composition has previously been investigated and some results are shown in Table 11. RCG grown on heavy clay soils produce the highest ash content. The most significant difference was in the silicon content of the material (Landström, Lomakka & Andersson, 1996; Burvall, 1997).

Table 11. *Mean values of nutrient and ash composition for RCG grown on heavy clay soils compared to RCG grown on humus rich sand soil. Delayed harvest, all values as percent of dry matter (Burvall, 1997).*

Soil type	N (%)	K (%)	Ca (%)	Mg (%)	Cl (%)	S (%)	Si (%)	Ash (%)
Clay	1.30	0.30	0.17	0.06	0.10	0.10	3.2	10.1
Humus/sand	0.60	0.12	0.15	0.04	0.05	0.10	0.56	2.2

Paper **I** describes the effect of variety, location, soil type, and yearly variation on the ash content, pulp yield, and fibre properties of delayed harvested, hand-fractionated RCG. Thirteen varieties of RCG were grown in eleven locations with varying soil and weather conditions in northern Europe. Data was collected from 1997 and 1998 to investigate yearly variation. The internode fraction of the RCG samples were analysed for ash content and pulp yield (kraft process). The drainage and fibre properties of he pulps were also analysed.

The results showed that the yearly variation had the greatest influence on the measured properties. The second year (1998) produced on average lower pulp yield and higher kappa number for the pulps. Data from Hemming (1998) also show a significant difference in pulp yield and kappa number of delayed harvested and fractionated RCG from 1995 and 1996 (Table 12). In that investigation, however, the second year gave higher pulp yield and higher kappa number. Variation in fibre properties between years has also been reported for wheat straw (Jacobs *et al*., 1998) and for kenaf (Cook *et al*., 1998). The variation in fibre properties for RCG and other annually harvested non-wood materials from one year to another is probably an effect of uncontrollable weather factors.

Table 12. *Kraft pulp yield and fibre properties of RCG harvested 1995 and 1996 (Hemming 1998).*

Property	RCG 1995 harvest	RCG 1996 harvest
Screened yield (%)	50	54
Kappa number	12.7	13.8
Fibre length (mm)	0.9	1.0
Fines (%)	35.7	37.5

The ash content of the internode fraction largely depended on the growing location and soil type. Paper **I** concluded that clay rich soils produce higher ash content, and sand rich soils produce lower ash content of the RCG internodes.

The effect of growing location and RCG variety on pulp yield and fibre properties could not fully be explained. The investigation indicated how the soil components affect the measured properties; for example, clay rich soil types produce poorer drainage properties and lower fibre coarseness. In addition, some varieties and locations were found less suitable for RCG short fibre production. The regression model based on RCG variety, growing location, and soil type did not contain enough information to predict pulp yield and fibre properties entirely (Paper **I**).

RCG handling before pulping

RCG has to be densified into bales or rolls before transporting and storing. The densifying should be as high as possible to keep transportation and storage cost low. A high degree of densifying also helps protect bales from weather damage by preventing the penetration of snow and rain. Generally, straw mills favour rectangular bales for the following reasons:

- Rectangular bales are easier to handle and transport;
- Rectangular bales are the most economic way to transport the material;
- Rectangular bales are easier to store and to protect from the weather than cylindrical rolls (Jayasingam, 1992).

Table 13. *Some bale dimensions and densities used for delayed harvested RCG in Sweden (Örberg, 2003).*

Type of bale	Dimensions (cm)	Density (kg/m^3)
Roll (round bale)	Diam. 120 × 120	140-190
	Diam. 140 × 120	140-190
Rectangular bales	230 × 80 × 90	180
	230 × 120 × 70	210
	250 × 120 × 90	150
	120 × 80 × 80	180

Storing the material as rolls is technically viable and economic. In the Finnish agrofibre project, storing rolls of RCG in covered stacks was the suggested method (Paavilainen *et al*., 1996). Storage in rectangular bales, however, has been tested in a full-scale trial for RCG pulp production and is the recommended method for large-scale use of delayed harvested RCG (Paavilainen *et al*., 1999). Storage of RCG in both rolls and rectangular bales for bio-energy production is being evaluated at the Biofuel Technology Centre in Umeå, Sweden (Örberg, 2003). Table 13 shows some dimensions and densities of RCG bales.

Pre-treatment

The fibrous materials for pulp production from cereal straw mainly come from the internodes of the stem. The sheath and the leaves do not contribute much as valuable materials for pulping. There is also a possibility that foreign materials such as sand, dust, grit, and small stones adhere to the stem of the raw material (Jayasingam, 1992). The main part of the fibre in delayed harvested RCG is found in the stem and the mineral contents are highest in the leaves. By removing the leaves, the ash and mineral contents can be decreased considerable and at the same time, the relative fibre content will increase in the remaining part (Finell, Hedman & Nilsson, 2000; Pahkala & Pihala, 2000; Paper **III**).

Cereal straw and RCG has to undergo a series of processes before it is made fit for cooking in the digester and converted to pulp. This process involves chopping, de-dusting, screening, cleaning, etc. The cleaning can be either in a dry or in a wet condition. Some non-wood raw material such as rice straw has a high tendency to collect sand and grit because of the growing conditions. In such cases, wet scrubbing helps remove foreign elements (Jayasingam, 1992).

The pre-treatment of non-wood materials can be compared to debarking and chipping of wood materials. Wood storage is often irrigated during summertime to improve the debarking efficiency and to keep a high raw material quality. During the winter, frozen wood also has to be treated by warm water or steam before debarking. These processes produce large amounts of wastewater that has to be treated. The bark fraction, which is used for energy production, also has a high moisture content (Kassberg, 1994; Jansson, 1998).

Wet cleaning has also been tested on RCG. It was found that the wet cleaning gave a higher pulp yield and improved bleaching especially TCF-bleaching. The losses during the cleaning process were about 10% (Paavilainen *et al.*, 1996b). Wet cleaning, however, produces large amounts of wastewater. Although a better cleaning of straw could be achieved in wet cleaning, there are many disadvantages with this system (Jayasingam, 1992):

- High steam consumption per ton of pulp as a result of cooking at low consistency;
- Non-uniformity in cooking due to variations in consistency on account of screw pressing fluctuations;
- Economics of operation is poor compared to dry cleaning due to high steam consumption and low output of pulp per unit digester, requiring a high capital investment on digesters.

Dry fractionation of RCG

Dry fractionation has the advantage of not producing wastewater and the reject fraction can be used as a valuable bio-fuel. Several methods for dry-fractionation of straw and other non-wood materials have been developed.

A method that uses air to separate chopped RCG provides a significant improvement of the pulp properties (Hemming, 1998). The Danish Fredericia straw mill used a similar dry fractionation method. The process equipment consists of a hammer mill that chops the RCG into smaller pieces that are then separated using air. The chopped RCG is fed into the separation tunnel where leaves and dust are separated from the stem fraction by the airflow. About 20% of the material is removed in this process. Pulp produced from the fractionated RCG produces higher yield, longer fibres, and less fines compared to untreated RCG.

Another method that has been successfully used for RCG pre-treatment is the disc mill dry fractionation process developed by UMS A/S in Denmark (Fuglsang & Löfqvist, 1993, Papatheofanous *et al*., 1995. Finell, Hedman & Nilsson, 2000). This dry fractionation process is described in Paper **II** and Paper **III**. The main process steps are shredding, chopping, grinding, and screening. In the shredding stage, the bales are disintegrated and the grass is transported to the hammer mill. In the chopping stage, the grass is pre-cut before it is transported to the disc mill. The hammer mill can be equipped with different screen sizes to vary the degree of cutting. In the grinding stage, the brittle parts of the grass such as leaves and leaf sheaths are ground to a fine meal and the tough parts of the grass, which mainly consist of internodes, are cleaved. The disc clearance can be varied during operation in order to change the fractionation efficiency. The grinding elements in the disc mill can also be varied to produce a tough, medium, or mild grinding effect. In the screening stage, the leaf meal and the internodes are separated. The separator can be equipped with different screen sizes to vary the degree of separation. For further refinement of the accepted fraction, a plan sifter can be added (two-stage separation). Figure 3 shows a block scheme with the main stages of the dry fractionation process.

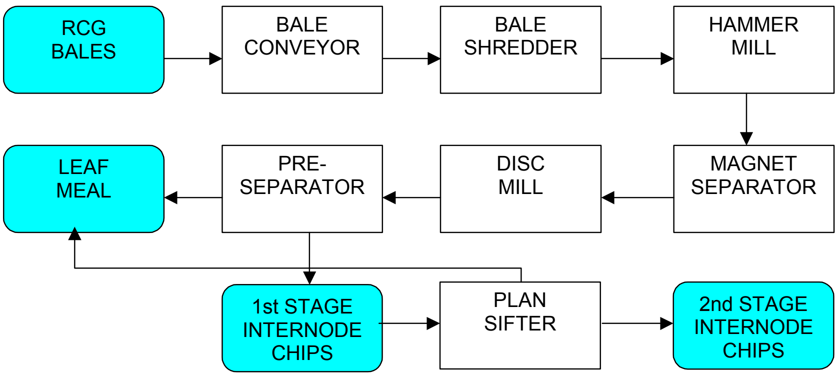

Figure 3. Schematic overview of the dry fractionation process developed by UMS A/S.

The results from dry fractionation trials with RCG are presented in Paper **III** and showed that the degree of separation was more important than the chemical charge, cooking time, or cooking process for the fibre properties. Fractionation with two-stage separation lowered the ash and silica content of the grass by almost 40%. The amount of fines was lowered, the drainage property of the pulp was improved, and the average fibre length was higher. The pulp yield of fractionated RCG was also 15% higher compared to untreated RCG (Finell, Hedman & Nilsson, 2000).

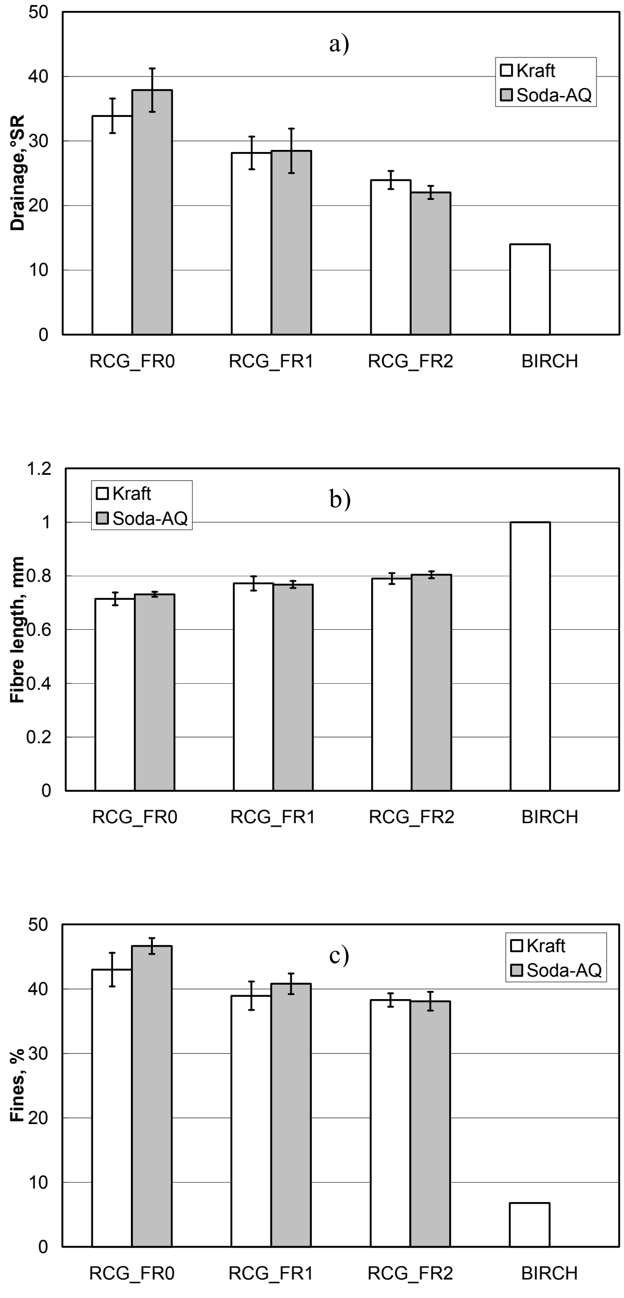

Figure 4. a) drainage, b) fibre length, and c) fines content of RCG pulp produced at different degrees of fractionation with the kraft and soda-AQ processes. RCG_FR0 indicates no fractionation, RCG_FR1 fractionation with one stage separation, and RCG_FR2 fractionation with two-stage separation The error bars indicate ± the standard deviation of the measurements.

Figure 4a-c shows the effect of dry fractionation on drainage, fibre length, and fines for RCG pulp produced with the kraft and soda-AQ processes (data from Paper **III**). For comparison, typical birch kraft pulp values have been added to the figures. RCG_FR0 indicates no fractionation. RCG_FR1 indicates fractionation with one stage separation. RCG_FR2 indicates fractionation with two-stage separation.

The disadvantage with fractionation of RCG before pulping is that a relatively large amount of raw material is removed with the reject fraction, which means that more raw material is needed to produce the same amount of pulp. If using the whole plant without fractionation, up to 50% of the raw material can be converted to papermaking pulp but at a lower quality. In this case, about 60% of the raw material was removed in the two-stage separation process, which means that only about 20% of the original raw material is converted to usable pulp. Optimisation trials on the dry fractionation process, however, has shown that it is possible to increase the accept fraction to about 60% without losing quality of the pulp (Olsson *et al*., 2001). Of course, the leaf content of the RCG entering the fractionation process will also influence the accept/reject ratio of the produced fractions. Thus RCG varieties with low leaf content are preferable for fibre production. However, the reject fraction can be used as a valuable bio-energy raw material either in the pulp mill together with bark or sold as pellets to external energy producers, and thus improving the overall economy.

Compression after fractionation

A pulp mill using RCG as raw material can either have pre-treatment of RCG integrated in the mill (centralised pre-treatment) or the pre-treatment can be located close to the farms (decentralised pre-treatment). The larger the production of RCG pulp the more likely it is that the raw material pre-treatment will be decentralised. Because RCG is harvested only once per year, all raw material needed for RCG pulp production has to be stored, and pre-processing combined with storage close to the farms seems to be a possible solution.

Dry fractionation of RCG produces two fractions: a stem (internode) fraction and a leaf fraction. Both fractions are of low density and need to be compressed before transport and storage. Transport cost of RCG is closely connected to the density of the transported material. Both fractions from the dry fractionation process can be compressed considerably (Hemming, 1998).With baling, in a special designed round bale press, of both fractions it has been possible to increase the density from 90 kg/m^3 to 180 kg/m^3 for the internode fraction and from 130 kg/m^3 to 210 kg/m^3 for the leaf fraction (Finell, Burvall & Olsson, 1998).

If the density of the internode fraction is further increased, then the risk of damaging the fibres increases. Briquetting is a common way to improve logistics for bio-fuels such as peat, sawdust, etc. Also RCG briquettes for energy production have been made. The most durable briquettes were made of the RCG stem fraction (Paulrud & Nilsson, 2001).

Paper **II** describes the compression of the internode fraction by briquetting and evaluates the impact of high pressure on pulp properties. The bulk density of fuel briquettes is about 600 kg/m^3, but for pulp production this was considered too high in view of the risk of mechanical fibre deterioration. The fuel briquettes are often compressed to such a degree that charring of the briquette surface occurs, which most likely damages the RCG fibres. The RCG briquettes for pulp production were produced at three different temperatures: 30°C, 60°C, and 90°C. The bulk density of the briquettes was adjusted to about 350 kg/m^3, which was supposed not to damage the fibres but still high enough to give considerable transport advantages compared to baled material.

Briquetting temperature had little or no effect on the briquette or pulp properties. The briquettes were, as expected, not as durable as fuel briquettes, which indicates that transport losses for pulp briquettes will be higher due to disintegration. The fibre properties of RCG pulp, however, were influenced by the pressure in the briquetting process. The briquetting process slightly but significantly increased the amount of fines in the pulp by 4-6% and produced paper that was less porous and denser. The advantages for transport and storage properties are shown in Table 14, which compares RCG at different degrees of compression to the conventional way birch is transported to the pulp mill. The table shows that by briquetting the internode fraction of RCG it is possible to transport three times as much (calculated as pulp) compared to baled or not compressed RCG. The transport capacity for briquetted RCG internodes is also two times as high as for birch logs (Paper **II**).

Table 14. *Transport capacity estimation for RCG at different compressing alternatives compared to birch.*

Pulp raw material	Density (kg/m^3)	Moisture (%)	Bark or leaf (%)	Pulp per vehicle (ton)
Freshly cut birch logs	500	50	10	9.0
RCG not fractionated in rect. bales	180	15	40	5.5
RCG internodes, no compression	100	10	0	5.4
RCG internodes, round bale	180	10	0	5.7
RCG internodes, briquetted	350	10	0	18.0

Assumptions: Swedish transport conditions, maximum load per vehicle 40 tons, maximum volume per vehicle 120 m^3, maximum 52 round bales per vehicle. Pulp yield is 50% for birch and RCG.

Pulping

Plant fibres are made up of cellulose (long un-branched chains of glucose), hemicelluloses (short chains of branched and un-branched polysaccharides, including galactose, mannose, and xylose), and lignin (a complex aromatic structure, which gives the inherent strength properties to plants). The ratio of these constituents and the chemical nature of the lignin and hemicelluloses varies according to plant species (Moore, 1996).

The main purpose of wood pulping is to liberate the fibres, which can be accomplished chemically, or mechanically, or by combining these two types of treatments. The common commercial pulps can be grouped into chemical, semi-chemical, chemi-mechanical, and mechanical types. These differ principally by the nature of the process used and the yield of pulp obtained. Typically, chemical processes produce pulp yields in the range 35-65%, semi-chemical 70-85%, chemi-mechanical 85-95%, and mechanical processes 93-97%. This yield difference highlights the fact that the chemical process effectively separates the cellulose from the lignin present, whereas the mechanical process converts all the constituents present. The choice of process will depend primarily on the nature of the material to be pulped and the grade of paper or board product desired (Sjöström, 1993).

Chemical processes are often used to produce fibres for strength and high quality printing products such as kraft paper or fine paper. Mechanical and chemi-mechanical processes produces pulp for lower grade products such as newsprint and board.

Chemical pulping processes

These are characterised by the use of chemicals to separate the lignin fraction of lignocellulosic materials from the cellulose. Chemical separation results in little or no effect on the fibre length. Kappa number is used to describe the extent of lignin removal in the cooking process. The kappa number is the quantity of potassium permanganate consumed by one gram of pulp under specific conditions. A low kappa number indicates low lignin content of the pulp sample.

The processes developed rely on the action of one or more radicals acting on the lignin compounds. Various improvements have been made to established processes to improve the selectivity (avoiding degradation of hemicellulose and cellulose) of the separation process. Chemical recovery of the active chemicals is an important economic and environmental consideration in any assessment of a pulping process (Moore, 1996). Table 15 shows some typical wood pulping conditions for alkaline pulping processes, and Figure 5 shows a schematic overview of the chemical recovery of a sodium hydroxide-based (alkaline) pulping process.

The kraft process is the dominant chemical pulping process. The process has been refined over the years to improve yield and chemical recovery. The kraft process has better selectivity and gives a higher pulp quality compared to the soda process. It has also almost completely replaced the sulphite process because of better chemical recovery system and the ability to use a broader range of raw materials. The pulping is performed with a solution composed of sodium hydroxide and sodium sulphide, "white liquor". According to the terminology, the following definitions are used. All the chemicals are calculated as sodium equivalents and expressed as weight-% of NaOH. (Sjöström, 1993).

Total alkali	All sodium salts
Active alkali	$NaOH + Na_2S + Na_2CO_3$
Effective alkali	$NaOH + ½ Na_2S$
Sulphidity	$100 \times NaOH / (NaOH + Na_2S)$ %

Table 15. *Alkaline pulping methods and conditions (Sjöström, 1993)*

Method	pH range	"Base"	Active reagents	Max. temp. (°C)	Time at max temp (h)	Softwood pulp yield (%)
Alkali (soda)	13-14	Na^+	HO^-	155-175	2-5	50-70[a]
Kraft	13-14	Na^+	HS^-, HO^-	155-175	1-3	45-55
Soda-AQ	13-14	Na^+	HO^-, AHQ^{-b}	160-175	1-3	45-55

[a] Hardwood, [b] Anthrahydroquinone

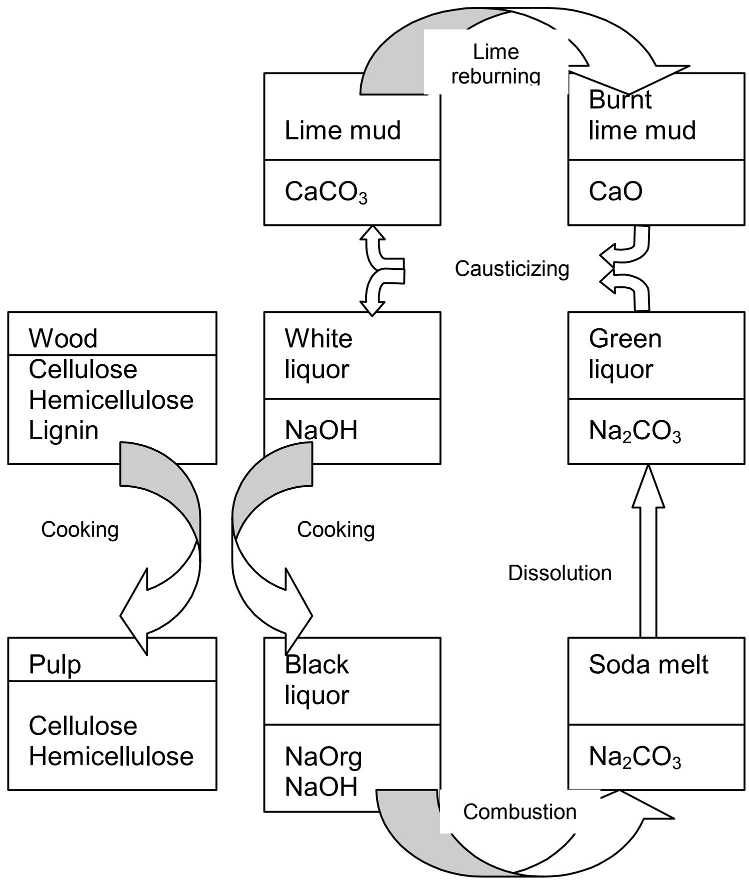

Figure 5. The main steps in the chemical recovery process for a NaOH-based pulping process.

The soda process is based on sodium hydroxide and is widely used in the processing of non-wood fibres. Unlike the kraft process, the soda process does not produce malodorous emissions. The process, however, does produce a pulp of lower quality compared to the kraft process because of lower selectivity. Major developments have centred on improving the yield from the process using additives such as anthraquinone (AQ). AQ accelerates the delignification while at the same time stabilising the polysaccarides from alkaline degradation. Sulphide in the kraft process is often replaced by AQ in alkaline sulphur-free processes (Sjöström, 1993; Moore, 1996).

The sulphite process is one of the earliest chemical processes and has developed into an array of variations used on wood and non-wood materials. This process has, however, become less favoured for economical reasons, and is almost totally replaced by the kraft process (Moore, 1996).

Mechanical processes

These are characterised by high yields, which result from the whole material or a major part of the material being converted into pulp by mechanical action. This pulp contains lignin, hemicelluloses, and cellulose. Mechanical processes use a lot of energy and create fibre damage. Development of the basic processes has sought to reduce energy consumption and improve fibre properties.

Stone groundwood (SGW) is the earliest mechanical process and, as the name suggests, grinds debarked logs by pressing them against a rotating stone. The grinding stone is showered with water to control the temperature and to remove the ground wood. **Pressurised groundwood (PGW)** has been developed from the SGW process to produce pulps with better strength properties and at a lower energy consumption by producing the pulp at a steam generated overpressure.

Refiner mechanical pulp (RMP) is manufactured by feeding the raw material, in the form of chips into the centre of a rotating disc refiner. Using wood chips has made it possible to broaden the raw material base as also saw mill chips can be used. Another advantage of this method is that the chips can be treated chemically before pulping. **Thermal mechanical pulp (TMP)** is a development of the RMP process where heat in the form of steam is applied to the raw material before the refining stage. This softens the chips and reduces fibre damage caused by the mechanical action (Moore, 1996).

Semi-chemical/chemi-mechanical processes

These processes involve a chemical pre-treatment of the raw material followed by refining. The major distinction between semi-chemical and chemi-mechanical processes is the concentration of the chemicals used and the conditions under which the pre-treatment takes place.

A semi-chemical process is the **neutral semi-chemical process (NSSC),** which typically involves up to 15% of sodium sulphite and 4-5% of sodium carbonate pre-treatment (cooking) of the raw material before mechanical defibration. This process often uses hardwood for the production of a high-yield pulp used to produce fluted paper.

Of the chemi-mechanical processes, the **chemi-thermo-mechanical pulp (CTMP)** has become the most popular. This process typically pre-treats the raw material with 1-4% of sodium sulphite. The CTMP pulp is stronger and brighter than TMP pulp, but the lower yield and chemical costs make this pulp more expensive (Jirvall *et al*., 1995; Moore, 1996). Table 16 shows some pulping processes used for non-wood materials.

Table 16. *Pulping processes for some non-wood plant fibrous materials (Kocurek & Stevens 1983).*

Raw material	Pulping process	Type of pulp	Pulp yield (%) Unbleached	Pulp yield (%) Bleached
Mixed cereal straw	Lime	Paper	55-65	-
Mixed cereal straw	Lime	Strawboard	70-80	-
Mixed cereal straw	Soda or kraft	Paper	55	50
Mixed cereal straw	Soda or kraft	Corrugating	67	-
Rice straw	Soda	Paper	42	39
Esparto	Soda	Paper	45-55	42-52
Sabai	Soda	Paper	-	-
Reeds	NSSC	Paper	52.7	48-50
Reeds	Soda	Paper	45.7-50.7	42-48
Reeds	Kraft	Paper	45.8-50.7	42-48
Reeds	Neutral sulphite	Corrugating	62	-
Papyrus	Soda	Paper	35-38	27
Bagasse (depithed)	Soda or kraft	Sack paper	60	-
Bagasse (depithed)	Soda or kraft	Paper	50-52	45-48
Bagasse (depithed)	Soda or kraft	Corrugating	70	-
Bagasse (depithed)	Soda or kraft	Linerboard	63	-
Bamboo	Soda	Paper	44-45	40-41
Bamboo	Sulphite	Paper	46-47	42-43
Seed flax, tow	Soda	Cigarette pap	42-45	40
Textile flax, tow	Soda	Paper	-	65
Jute	Soda	Paper	62	58
Kenaf	Soda or kraft	Paper	45-51	40-46
Abaca (Manila)	Soda or kraft	Paper	45-54	43-52
Sisal (Agave)	Soda	Paper	69	60
Cotton linters	Soda or kraft	Paper	-	70
Cotton linters	Soda or kraft	Dissolving	-	65
Cotton rags	Lime	Paper	-	70
Cotton rags	Soda	Paper	-	70

Chemical pulping of RCG

The most common chemical pulping method for non-wood raw materials is soda cooking with or without anthraquinone (AQ). Kraft cooking is used for bamboo and reed. Integrating the non-wood fibre line into a mill cooking wood will bring a scale benefit and improve the production efficiency.

In addition, solvent pulping methods have been tested for non-wood raw materials. Unfortunately, these processes are not economically feasible without the sales of co-products. For example, the spent liquor can be used as a fertiliser. In capital-poor countries, this would be most appropriate; however, the environmental impact of using such fertilisers needs further study (Paavilainen, 1998b).

For RCG a number of different chemical pulping methods have been investigated. Table 17 summarises some of the methods used for RCG. In addition to the most common methods (soda-based and kraft), ethanol-based, peroxyformic acid (milox), sulphite, and lime-phosphate-oxygen methods have been used. These different methods produce pulp within a wide range of pulp yield, kappa number, drainage, and fibre length. Interesting is that also within the same cooking method (kraft) the pulp properties vary considerably.

In Paper **III**, the kraft and soda-AQ processes have been compared with RCG pulp production. The kraft process was more efficient for delignification and defibration. There was no difference in the measured fibre properties (Figure 4a-c) between the two processes with the exception of fines for non-fractionated RCG (RCG_FR0) where the soda-AQ process gave a higher level. Of the investigated process variables, the alkali charge (EA) had the greatest influence on the measured properties.

Figure 6a-b shows the effect of alkali charge and cooking time on pulp yield and Figure 7a-b the effect of alkali charge and cooking time on kappa number for RCG pulp produced with the kraft and soda-AQ processes. The cooking time has little effect on the pulp yield for both processes investigated. The kappa number, however, as expected depends on both alkali charge and cooking time.

Table 17. *Some chemical pulping processes and fibre properties for RCG found in the literature*.

Source	Harvest method	Fract. of raw mtrl	Pulping process	Pulp yield (%)	Kappa no.	Drainage (°SR)	Fibre length (mm)
Feng and Alén, 2001	-	-	soda-AQ	58.7-47.6	38.9-12.3	-	-
Finell, Hedman & Nilsson, 2000	delayed	no	kraft	47.5	15.9	33.5	0.72
Finell, Hedman & Nilsson, 2000	delayed	yes	kraft	54.5-50.8	12.0-9.7	28.0-23.0	0.85-0.77
Fuglsang and Löfqvist, 1993	delayed	no	kraft	48	19.0	39	0.90
Fuglsang and Löfqvist, 1993	delayed	yes	kraft	53	10.7	23	1.05
Hemming, 1998	delayed	no	kraft	45	11.7	-	0.6
Hemming, 1998	delayed	yes	kraft	54-50	13.8-12.7	-	1.0-0.9
Hemming, Järvenpää & Maunu, 1994	traditional	yes	soda-AQ	44.6	11.0	20.7	0.68
Hemming, Järvenpää & Maunu, 1994	traditional	no	soda-AQ	41.7	15.0	34.2	0.63
Håkansson, Sjöberg & Ahlgren, 1996	traditional	no	ethanol-water	45-40	97-46	45	-
Håkansson, Sjöberg & Ahlgren, 1994	-	yes	soda	44-43	19.3-17.8	40	-
Håkansson, Sjöberg & Ahlgren, 1994	-	yes	ethanol-soda	49-45	15.0-12.5	40	-
Olsson, Torgilsson & Burvall, 1994	delayed	no	kraft	48.5	19.0	-	0.89
Olsson, Torgilsson & Burvall, 1994	delayed	yes	kraft	53.4-51.0	14.2-10.7	-	1.05-0.98
Paavilainen *et al*., 1999	delayed	no	kraft	49.0	11.9	32	0.63
Paavilainen *et al*., 1999	delayed	yes	kraft	54.0	9.3	25	0.71
Paavilainen, Tulppala & Balac, 1996	-	-	soda-oxygen	64.1-62.1	30.1-22.5	-	-
Paavilainen and Torgilsson, 1994	traditional	-	kraft	48-38	-	-	-
Paavilainen and Torgilsson, 1994	delayed	-	kraft	53-50	9	31-20	0.90-0.80
Papatheofanus *et al*., 1995	-	no	soda	66.5	64	-	-
Papatheofanus *et al*., 1995	-	yes	soda	73.0	59	-	-
Seisto and Poppius-Levlin, 1995	-	no	milox	50.9-45.5	24.0-11.2	-	-
Thykesson, Sjöberg & Ahlgren, 1997 and 1998	-	yes	kraft	38.7	36.7	65	0.80
Thykesson, Sjöberg & Ahlgren, 1997 and 1998	-	yes	ethanol-soda	39.0	18.1	48	0.80
Thykesson, Sjöberg & Ahlgren, 1997 and 1998	-	yes	bisulphite	39.4	62.7	52	0.80
Thykesson, Sjöberg & Ahlgren, 1997 and 1998	-	yes	ethanol-water	39.6	86.0	48	0.80
Yilmaz *et al*., 1995	delayed	-	lime-phosp.-O_2	59.3-58.8	32.3-27.4	-	-

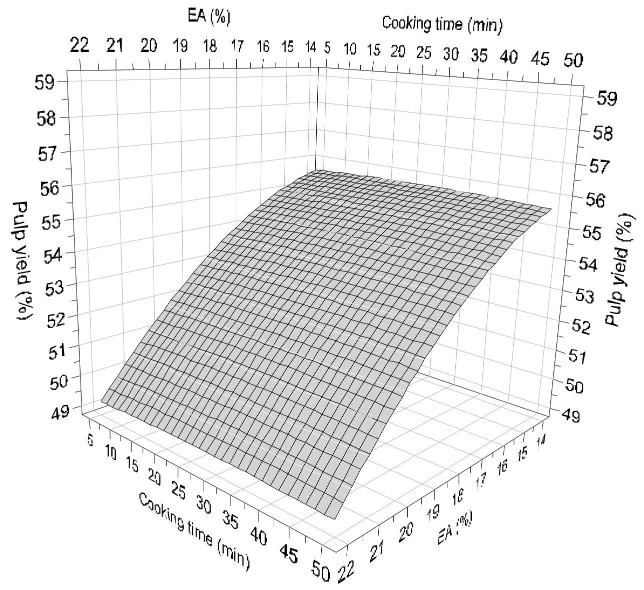

Figure 6a. Screened pulp yield as a function of alkali charge and cooking time for the kraft process. Two stage fractionated RCG.

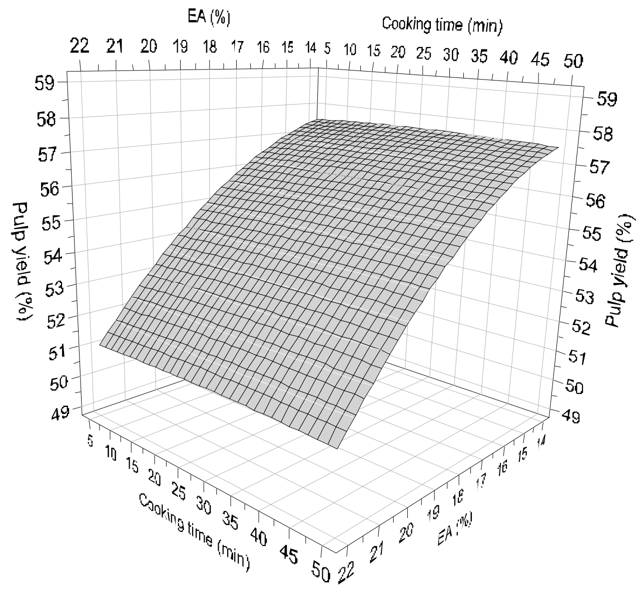

Figure 6b. Screened pulp yield as a function of alkali charge and cooking time for the soda-AQ process. Two stage fractionated RCG.

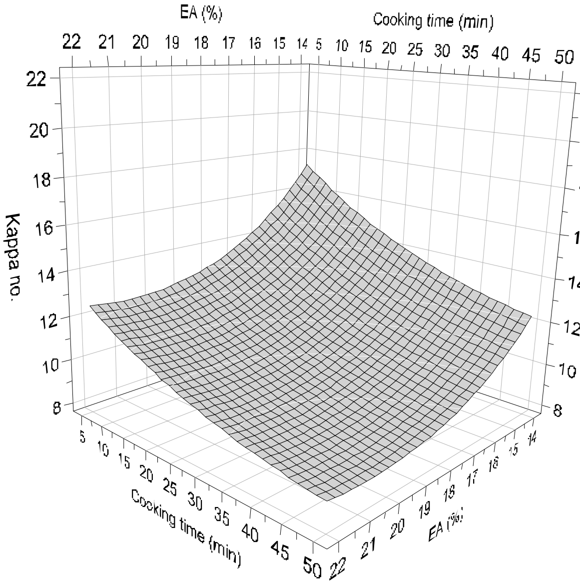

Figure 7a. Kappa number as a function of alkali charge and cooking time for the kraft process. Two-stage fractionated RCG.

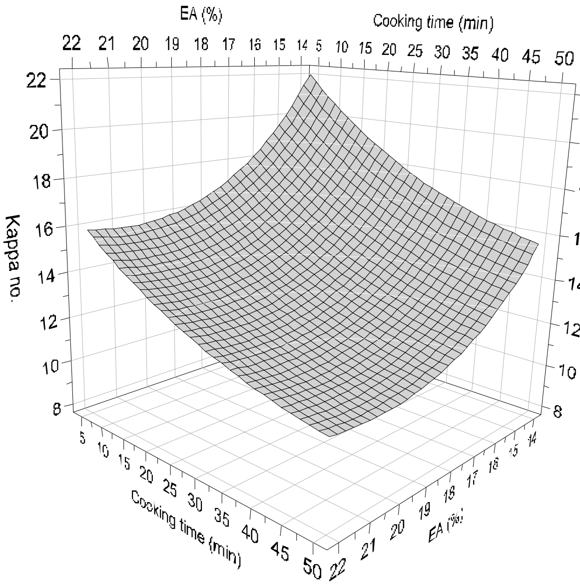

Figure 7b. Kappa number as a function of alkali charge and cooking time for the soda-AQ process. Two-stage fractionated RCG.

Pulp properties of RCG

Some pulp properties of delayed harvested and fractionated RCG are compared to oxygen delignified birch pulp in Table 18. The variation between RCG pulp produced under different conditions are considerable.

Table 18. *Comparison between kraft pulp properties for RCG produced under different conditions compared to oxygen delignified birch pulp.*

Property	Lab. scale RCG pulp[1]	Lab. scale RCG pulp[2]	Mill scale RCG pulp[3]	Mill scale Birch pulp[3]
Kappa no.	9.2	9.1	6.8	9.2
Drainage (°SR)	30	28	21	22
Sheet density (kg/m^3)	701	724	588	697
Tensile index (kNm/kg)	76.8	96.0	49.1	62.7
Tear index (Nm^2/kg)	5.43	7.70	7.80	8.22
Burst index (MN/kg)	4.00	6.00	3.28	3.99
Opacity (%)	-	-	97.5	85.7
Light scatt. coeff. (m^2/kg)	-	-	39.5	28.7

[1] Data from Paper **II**
[2] Data from Finell, Olsson & Backlund (2002)
[3] Data from Paper **IV**

The sheet density for mill procuced RCG pulp is much lower compared to laboratory produced RCG pulp. Large variations in the strength properties of RCG pulp can also be detected. In addition to differences in the raw material and degree of fractionation, the mill scale pulp was “overcooked”. In this case, more of the hemicelluloses were dissolved during the cooking, lowering the sheet density and the tensile strength of the pulp. Another possible explanation is that the pulps were washed in different ways and some fine material was removed, affecting the sheet density and strength properties.

The results, however, indicate that a wide range of pulp properties can be obtained from RCG by adjusting the parameters in the cooking process.

Silica removal

Silica in the raw material is a problem when using non-wood raw materials. The silica content of grasses is up to 100 times higher than in wood materials. The silica is dissolved in the black liquor during alkaline (kraft or soda-based) cooking and causes problem in the chemical recovery: harmful precipitates on heat transfer surfaces, poor settling characteristics during causticising, lime re-burning difficulties, and decreased heat economy. Two methods were found suitable for desilication in the Finnish agro-fibre project and the EU reed canary grass project.

Desilication of weak black liquor at the beginning of the recovery cycle helped avoid problems in later stages. In this process, black liquor is carbonated by flue gasses to a pH level of about 10, where calcium silicate precipitates. Commercial installation of this process shows that the three-stage desilication plant has a desilication efficiency of 80%, and the removed silica sludge contains 90% SiO_2, 0.5% lignin, and 0.1% sodium.

Two-stage causticizing, where calcium silicate precipitates in the first stage and can be removed from the process. Possible problems in the evaporation plant can be avoided by using a special heat treatment for black liquor. Also a combination of carbonation and two-stage causticizing could be a solution for economical desilication (Paavilainen, Tulppala & Balac, 1996; Olsson *et al*., 2001).

Bleaching

After cooking, kraft pulp is a deep brown colour because chemical changes in the lignin, which from the beginning was more or less colourless. In order to make a white paper, the pulp has to be bleached. There are two main types of bleaching: lignin-removing bleaching and lignin-preserving bleaching.

Lignin-removing bleaching is a continuation of the dissolving of the lignin during the cooking process but with more gentle chemicals and at a lower temperature. The process converts the lignin into soluble substances that can be removed by washing and the natural white colour of the cellulose fibre emerges. Lignin-removing bleaching is the most widely used method for chemical pulps.

Lignin-preserving bleaching, uses chemicals that make the lignin lighter in colour and are used without removing the lignin from the pulp. Lignin-preserving methods are mostly used for mechanical pulp in which all the lignin remains.

Brightness for pulp and paper is measured in ISO brightness, which is expressed as a percentage of absolute whiteness. Unbleached softwood kraft pulp has a brightness of about 26% ISO. Bleached pulps have a brightness from 70% ISO to more than 90% ISO. Newsprint has a brightness of 65-70% ISO. Printing and writing papers have brightness between 85% and 90% ISO and have to be manufactured from highly bleached pulps.

It used to be common to use chlorine gas as bleaching chemical because this was an effective and inexpensive bleaching agent; however, emissions of chlorinated organic compounds (AOX) are harmful to the organisms in rivers, lakes, and seas. The consequence of this was that research and development work on bleaching became concentrated on reducing the use of elemental chlorine. New technology has been developed that replaces elemental chlorine in the bleaching process. For kraft pulp, there are several steps in this development: modified cooking, oxygen delignification, bleaching with chlorine dioxide instead of with elemental chlorine, peroxide bleaching, and bleaching with ozone. Bleaching without elemental chlorine is called ECF (Elemental Chlorine Free) and bleaching without chlorine chemicals is called TCF (Totally Chlorine Free). Table 19 shows some common stages in ECF and TCF bleaching and their symbols (Jirvall *et al*., 1995).

Table 19. *Some common bleaching stages and their symbols*

Bleaching stage	Symbol
Oxygen	O
Chlorine dioxide	D
Alkaline extraction	E
Peroxide	P
Chelating	Q
Ozone	Z

Bleaching of RCG pulp

RCG pulp used in high quality printing papers has to be bleached. ECF (elemental chlorine free) and TCF (total chlorine free) bleaching methods are commonly used to bleach birch pulp. Table 20 shows the conditions in ECF and TCF bleaching for delayed harvested reed canary-grass compared to birch.

In a laboratory scale study by Paavilainen & Tulppala (1996) it was found that there was no difference between the bleachability of delayed harvested and dry fractionated RCG pulp and oxygen delignified birch pulp in ECF bleaching. If an oxygen stage was added to TCF bleaching of RCG pulp, it was possible to reach the same brightness as with TCF bleaching of birch pulp. To reduce costs it was suggested that RCG pulp is bleached together with oxygen delignified birch pulp with ECF bleaching.

Table 20. *Bleaching conditions for RCG and birch with ECF and TCF methods (Paavilainen & Tulppala, 1996).*

	RCG ECF	RCG TCF	Birch ECF	Birch TCF
Sequence	D(E/O)DD	OQP(Z/Q)P	OD(E/O)DD	OQP(Z/Q)P
Kappa no after cooking	10	10	15	15
Kappa no after O_2 stage	-	n. a.*	10	10
ClO_2 (act. Cl), kg/ADt	38	-	38	-
NaOH, kg/Adt	14	35	14	35
O_2, kg/ADt	5	n. a.*	15	11
H_2O_2, kg/ADt	-	25	-	25
O_3, kg/ADt	-	4	-	4
Yield, %	96.0	95.0	94.5	94.0
Brightness, % ISO	87	87	87	87

* Data not available

Reed canary grass pulp produced in a sawdust digester in full scale (Paavilainen *et al*., 1999) was also bleached with a short TCF sequence. Paper **IV** describes the optimisations trials for QP (chelating peroxide) bleaching of mill-produced RCG pulp. The trials showed that it was not possible to reach the same brightness as for birch pulp, probably because the RCG pulp contained more metal ions (mainly Fe) than birch pulp that disturbed the peroxide bleaching. The brightness of RCG pulp did not reach the desired goal (80% ISO) even with a peroxide dosage of 60 kg/t. Birch pulp reached a brightness of more than 80% ISO at a peroxide dosage of 40 kg/t. Despite the lower brightness, the bleached RCG pulp produced some interesting optical properties in the end product. Figure 8 shows the effect of peroxide dosage on RCG pulp brightness at different pH levels.

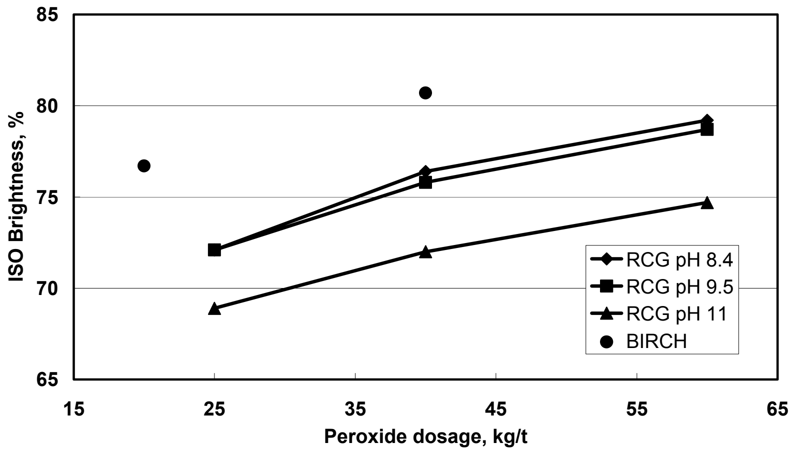

Figure 8. Effect of peroxide dosage on brightness for RCG pulp at different pH levels. Some typical values for birch pulp have been added for comparison.

The bleaching trials indicate that RCG pulp should be bleached by an ECF sequence. The ECF sequence can handle RCG pulp with a high metal ion content and produces a higher yield. ECF bleaching does not require oxygen delignification of the RCG pulp, which reduces a process step. This will make ECF bleaching more economical than TCF bleaching.

Papermaking

Paper consists of cellulose fibres that are bonded to each other in a network that forms a sheet. By choosing raw materials and pre-treatment of the fibres in different ways, papers that have widely differing properties can be obtained. Many paper mills have their own pulp mills, and in such cases the pulp is pumped directly from the pulp mill to the paper mill (integrated production). Those paper mills that lack their own pulp mills purchase the pulp in bales, which have to be dissolved in water before processed into paper (non-integrated production).

The papermaking process

The papermaking process can be divided in four main stages: stock preparation, de-watering, pressing, and drying. These steps can be followed by finishing stage, which can involve smoothening, surface sizing, coating, cutting, re-winding, wrapping/packing, etc. Paper machines differ in appearance, depending on the type of paper being made; however, all paper machines have the same main components: the wet section, the press section, and the dryer section.

The fibres in the paper pulp are mixed with water and pre-treated in a suitable way. This part of the process is called stock preparation. Often different types of paper pulp are mixed together in order to give the paper the desired properties. Long softwood fibres provide strength for the paper and short hardwood fibres produces good optical and printing properties. Usually, this mixing is done in conjunction with stock preparation. The cellulose fibre must be treated so that it becomes more water-absorbent and can be more easily bonded to another fibre. This is where the cellulose fibres pass through a refining (beating) process, which is vital in papermaking. Before refining, the fibres are stiff, inflexible, and form few bonds. The refining process has the effect of cutting, opening-up, and de-clustering the fibres. In this state, the fibres have greater surface area, which significantly improves the fibre bonding. The properties of the paper are directly related to the refining process. Mechanical pulp and pulp made of recycled fibre are not normally beaten as they already have sufficiently good sheet-forming properties.

Chemicals are added to the stock to control its pH. Fillers such as clay, talc, and calcium carbonate are added to enhance the brightness and opacity of the paper. Many types of fine paper contain up to 30 percent filler. Size is also mixed into the stock to increase the surface bonding strength and to reduce the water absorption capability of the paper. Alum (aluminium sulphate) is added to make it easier for the size particles to adhere to the fibres. Starch is also added to enhance the strength and stiffness of the paper. Other types of additive are colourings, de-foamers, and retention agents, which improve the ability of the fine fraction and the filler to remain on the wire.

In the wet section of the paper machine, the stock is de-watered on one or more wires. The highly diluted stock (0.2-1%) flows out onto the wire from a head box and is de-watered. The stock leaves the wire as a web of paper with a dry solid content of about 20 percent.

De-watering of the paper web continues in the press section; the web is pressed between press rolls. Usually the press section consists of three or four such press roll nips in which the dry solids content of the paper increases every step. After the final press roll nip, the dry solids content is about 30-50 percent. The presses are usually fitted with press felts, which distribute the pressure on the paper web and remove water.

In the dryer section, the paper web is dried to a dry solids content of about 95%. This is accomplished by dryer wires, which press the paper web against steam-heated drying cylinders. After leaving the dryer section, the paper is often passed through a finishing machine, which consists of a stack of steel rolls. As the paper passes through the nips between the rolls, its surface is made smooth.

The paper can be surface-treated in different ways. To reduce the amount of dust coming from the surface of the paper in the printing presses, the paper is surface sized. This is done with starch in sizing presses, which are located in the dryer section or in a separate station. When enhanced brightness and printability are required, the paper is covered with a coating of kaolin, calcium carbonate, or titanium dioxide. The coating can be applied, as can surface sizing, either in the paper machine or in a separate station.

Before the paper is delivered, the reel on the reeling drum is divided into smaller reels and wrapped. Some paper is delivered in the form of sheets of different formats after cutting in a sheet cutter (Jirvall *et al*., 1995).

Paper production from RCG

In the papermaking process for wood fibres, the refining (beating) stage gives the paper its strength properties. RCG fibres, however, do not behave in the same way as birch fibres in this process. RCG fibres did not develop tensile strength to any appreciable extent upon beating, and the tear strength was almost constant or not influenced by beating (Thykesson, Sjöberg & Ahlgren, 1997). Strength properties of unbeaten fractionated and delayed harvested RCG were, however, in the same class as for beaten birch pulp although at lower sheet density (Finell, Olsson & Backlund, 2002).

Unbeaten RCG pulp has a good bonding ability, and there is no need to refine RCG pulp to be used in paper production. Refining will only deteriorate the drainage properties of the RCG pulp. Refining RCG pulp together with birch pulp preserves the fibre length and reduces energy consumption in the refining process (Paavilainen & Tulppala, 1996). Below are two examples of paper grades (fine paper and white-top liner paper) that successfully use RCG pulp.

Fine paper

The role of short-fibre pulp in fine paper (high quality writing and printing paper) is to improve printability of the paper. The strength requirements for runnability on the paper machine can be adjusted by adding long softwood fibres (Paavilainen & Tulppla, 1996).

In the study by Paavilainen & Tulppla (1996), bleached pulp from delayed harvested and fractionated RCG was used as the short fibre component in base paper for fine paper production in pilot-scale trials. The fibre mixture of the base paper contained 30% bleached softwood pulp and 70% bleached short-fibre pulp from birch or RCG. The short-fibre content varied with different mixtures of birch and RCG pulp, ranging from 0-70%. The paper also contained 15% of calcium carbonate filler and the retention aid dosage was kept constant. Some of the base paper was coated and some surface-sized. No runnability problems were detected on the slow pilot-scale paper machine when the amount of RCG was increased up to 70%. In addition, the sheet dryness after pressing and the moisture content after drying stayed constant when the amount of RCG fibres in the paper was increased. Retention and formation of the paper also stayed constant with increasing RCG ratio.

The paper properties showed that the tensile and especially the tear strength of the base paper somewhat decreased with increasing RCG fibre content. The optical properties, however, were improved with increasing RCG fibre content. The properties of the coated paper showed that the birch pulp could be replaced by RCG pulp without changes in the functional properties of the paper. In addition, for surface-sized paper, the major part of birch pulp in the base paper could be replaced by RCG pulp. Offset printing tests of the coated and surface-sized RCG containing papers showed that the printing characteristics were comparable to those of wood based paper (Paavilainen & Tulppala, 1996).

White-top liner paper

White-top liner (WTL) paper is beside fine paper a paper grade where hardwood short fibre materials are used to give a good printing surface. WTL is a multi-layer liner of a bleached top layer and an unbleached base layer and is typically used as the surface layer of corrugated board.

Paper **IV** describes the use of RCG pulp as a short-fibre component in WTL. Pulp from delayed harvested and fractionated RCG was produced in a full-scale sawdust digester (Paavilainen *et al.*, 1999). The unbleached RCG pulp had very good optical properties (opacity and light scattering) compared to oxygen delignified birch pulp (Table 18), but TCF bleaching of the RCG pulp did not give the same brightness level as birch pulp (76.3% ISO compared to 80.3% ISO for birch). An interesting property of the unbleached RCG pulp was that the sheet density and porosity were lower compared to birch pulp.

Anisotropic sheets of WTL were produced with an unbleached 100% softwood kraft fibre base and a bleached top layer containing 50% softwood fibre and 50% short fibre from birch and/or RCG. The sheets were treated in a laboratory calender under conditions comparable to those in the paper machine when manufacturing WTL.

The results shows that the tensile strength of the WTL sheets were lowered by about 10% when all birch pulp was replaced by RCG pulp. The optical properties, however, were very interesting. Despite the fact that RCG pulp had lower brightness than birch pulp, increasing RCG content positively influenced the brightness and lightness values of the WTL sheets. This shows that it is possible to reduce the amount of expensive bleached fibres in the top layer of WTL if RCG pulp with the same brightness as bleached birch pulp is used.

Experimental design and data analysis

In multivariable heterogeneous reaction processes (such as pulping processes), the use of factorial designed experiments are very useful to statistically investigate the influence of process variables on response variables such as kappa number and pulp yield. The complex effects of the process variables on each response variable can be analysed by response surface methodology (Myers and Montgomery, 1995).

When using the response surface methodology approach on processes with qualitative factors or if the experimental region is an irregular polyhedron, classical factorial designs cannot be used. In these cases, a computer-generated “D-optimal” design might be useful. D-optimal means that the design maximises the information in a selected set of experimental runs with respect to a stated model (Eriksson *et. al.*, 2000).

PLS compared to MLR

In Paper **III**, the influence of dry fractionation of RCG and the process parameters effective alkali and cooking time on pulp yield, reject and kappa number for the kraft and soda-AQ processes have been investigated. The experiments were based on a D-optimal design but as additional experiments and qualitative factors were added, the experimental region became irregular and the regression models to find the relationship between process variables and pulp properties became more complex. Another factor that complicated the calculation of regression models was the fact that some data was missing in the response matrix (drainage, fibre length, coarseness, and fines) that limited the use of traditional regression models.

Two methods – MLR (multiple linear regression) and PLS (partial least squares) – were used to find the relationship between the variables and the measured properties. MLR is the traditional method used for designed experiments, but this method has some limitations compared to PLS.

When several responses have been measured, it is useful to fit a model simultaneously representing the variation of all responses to the factors. This is possible with PLS because PLS deals with many responses by taking their covariances into account. MLR is not as efficient in this kind of situation because separate regression models are fitted for each response. In addition, PLS compensates for distorted experimental design. That is, PLS handles distorted designs more reliably than MLR because MLR assumes perfect orthogonality. PLS also has the advantage of handling missing data in the response matrix. MLR cannot handle missing data efficiently; therefore, each experiment for which data are missing must be omitted from the analysis (Eriksson *et al.*, 2001).

The R^2 and Q^2 parameters can be used to evaluate the models. R^2 is a measure of how well the regression model can be made to fit the data. R^2 varies between 0 and 1, where 1 indicates a perfect model and 0 no model at all. Q^2 is a measure of the predictive power of the model. Q^2 has an upper limit of 1 and a lower limit of minus infinity. Q^2 is obtained by repeating the calculations of the regression model several times with different objects kept out of the calculation of the model. For a model to pass this diagnostic test, both R^2 and Q^2 should be high and preferably not separated by more than 0.2-0.3. Generally, a $Q^2 > 0.5$ is regarded as good and $Q^2 > 0.9$ excellent (Eriksson *et al.*, 2000).

Table 21 shows a comparison between regression models based on MLR and PLS for pulp yield, screening reject and kappa number from Paper **III**. MLR was used for each pulping process and a separate model was calculated for each response. In PLS modelling, both pulping processes were included in the model and all responses were modelled simultaneously.

Table 21. *Comparison between MLR and PLS modelling of the kraft and soda-AQ pulping processes.*

Regression model	Pulping process	Pulp yield R^2/Q^2	Screening reject R^2/Q^2	Kappa no. R^2/Q^2
PLS	Kraft	0.82/0.74	0.83/0.81	0.81/0.78
	Soda-AQ	0.82/0.74	0.83/0.81	0.81/0.78
MLR	Kraft	0.92/0.89	0.98/0.96	0.92/0.86
	Soda-AQ	0.76/0.69	0.93/0.90	0.78/0.70

Table 21 shows that MLR modelling of the kraft process gives almost perfect models for the responses shown. MLR modelling of the soda-AQ process also produced good models for the responses but not as good as for the kraft process. PLS modelling gave good models of all responses, and it seems that PLS modelling of all responses simultaneously stabilises the model in this case.

The reason for choosing PLS modelling in Paper **III** was, however, the ability to model responses with missing data and the ability to get the overview and interpret the model with the use of PLS score and PLS weight plots. The PLS score plot contains information about the observations and their similarities/dissimilarities with respect to the given problem and model. The PLS weight plot gives information about how the variables combine to form the quantitative relation between X and Y (Eriksson *et al*., 2001).

Conclusions

RCG is a sustainable, high yielding crop suitable for the Nordic countries when the delayed harvesting method is used. Delayed harvested RCG is already successfully used as a fuel raw material and this sector is rapidly expanding. In this work, some aspects on reed canary-grass for short fibre pulp production have been studied. The work investigates quality variations of the raw material, transportation, storage, refining of the raw material by dry fractionation, chemical pulping, bleaching and paper production. Many parts of the work have been tested in full-scale applications. Conclusions from this work are summarised below.

- The ash content of delayed harvested reed canary-grass depends on the growing location and soil type. Clay rich soil types produce high ash content of the grass and poor drainage properties of RCG pulp (Paper **I**).

- The yearly variation in fibre yield, kappa number, and fibre properties are considerable. By selecting RCG varieties suitable to the growing location, it is likely that the variations can be reduced (Paper **I**).
- The pulp quality is also affected by the leaf and leaf sheath content. By removing leaves and leaf sheaths, the pulp properties are improved and the quality variations reduced. Removal of leaves and sheaths can be done by dry fractionation (Paper **III**).
- The dry fractionation process produces a bulky internode fraction for pulp production. If the raw material is not dry fractionated at the pulp mill, the internode fraction can be compressed by briquetting to improve transport and storage (Paper **II**).
- Briquetting has a slightly negative effect on the pulp properties of RCG (produces more fines), but the transport and raw material storage benefits are substantial (Paper **II**).
- When RCG pulp is produced with the kaft or the soda-AQ process, the degree of raw material fractionation is the most important factor for the pulp properties (Paper **III**).
- Using the kraft process, it is possible to obtain lower kappa numbers of the pulp compared to the soda-AQ process. The soda-AQ process, on the other hand, produces a slightly higher pulp yield (Paper **III**).
- RCG pulp is more difficult to bleach than birch pulp with a TCF process. RCG pulp is recommended to bleach with an ECF process (Paper **IV**).
- RCG pulp can be used as a short fibre component in white-top liner paper. It is possible to reduce the amount of expensive bleached fibres in white-top liner if bleached RCG pulp is used instead of bleached birch pulp (Paper **IV**).

Future research

The cultivated area of RCG in Sweden is now 430 ha (Eriksson, 2003) and in Finland 2,700 ha (Sahramaa, 2003). By the year 2005, two projects aim to increase the cultivated area of RCG for bio-fuel production: 3,000 ha in northern Sweden (Anonymous, 2003) and 4,000 ha in Finland (Myntti, K., 2003). These projects will give valuable information about handling and storage of RCG. The next logical step is to further increase the cultivated area of RCG, for use as a short fibre raw material for the pulp and paper industry.

The most realistic way to start RCG pulp production is to modify an existing kraft sawdust line for RCG pulp production. A modified sawdust line with a capacity of 10,000 tons pulp per year would require about 4,000 ha of RCG. The modification would include covered bale storage, a new handling system (including dry fractionation) for RCG, modifications of the feeding line and digester, and a silica removal plant to treat the black liquor. This can be done with reasonable costs (Paavilainen *et al*., 1999).

By using briquetted RCG the raw material supply radius can be considerably increased. Large-scale RCG pulp mills (100,000 tons of pulp per year or more) could use briquetted RCG produced for example in the Baltic countries. Import of birch from these countries is profitable and by using briquetted RCG the transport capacity, on a fibre basis, can be doubled using the same transport volume. Calculations on the use of imported briquetted RCG for pulp production should be made.

The research on RCG as a fibre raw material has mainly been concentrated on a few processes and end products. There are most likely more possibilities for RCG as a raw material in products ranging from fibreboards to dissolving pulp. Future research should concentrate on the soda-oxygen pulping process. This method can considerably reduce the amount of silica in the spent cooking liquor. Development of small-scale, environmental friendly processes for pulp production from RCG and other agriculturally produced raw materials is needed. The use of agriculturally produced fibres in different composite materials is a very interesting research area. The use of precipitated calcium silicate in different products has to be investigated.

It should also be kept in mind that the pulping processes and pulp products that have been developed during the last 150 years have mainly focused on wood as raw material in the Nordic countries. By replacing a part of the wood raw material with RCG, new opportunities both for the agricultural sector and the pulp and paper industry will emerge.

Acknowledgements

I wish to express my sincere gratitude to my supervisor, professor Calle Nilsson for encouraging me to write this thesis. Without the support of Calle, this thesis would never have been completed. I also would like to thank Rolf Olsson, who introduced me to reed canary-grass and the delayed harvesting method and convinced me of the advantages for pulp and paper production of this grass. Thanks to my co-supervisor Roland Agnemo and to Stefan Svensson and Ove Rehnberg for being my contacts to the world outside the university. A special thank to Björn Hedman for invaluable laboratory assistance, Paul Geladi for constructive comments on the data analysis, Jan Burvall for help with arrangement of baling trials and Shaojun Xiong for taking care of my hemp project. I also want to thank all my colleagues at SLU Röbäcksdalen.

I would like to thank the participants of the EU reed canary-grass project:

- The crop producers, who supplied me with reed canary-grass samples from all parts of Northern Europe, despite a cryptic coding system and confusing instructions: Staffan Landström, Timo Mela, Hannele Sankari, Mika Hemming, Jørgen Mortensen, Uffe Jørgensen, Nasir El Bassam, Katrin Jacob, Wolfgang Bacher, Dudley Christian, David Hides, Llinos Jones, Ian Morrison, Derek Stewart, Mike Jones, Bengt Andersson, Eva Lindvall and all other involved that I have forgotten the names of.
- The chemical pulping consultants: Leena Paavilainen and Jorma Tulppala for interesting discussions and for making good reports of my not always so well structured contributions.
- The fractionation specialists: Jan Schade, Bo Löfqvist, Henning Fuglsang and the staff at the Bioraf plant on Bornholm for separating countless RCG samples in different fractions. Using the pelletised leaf fraction as camel feed in Egypt was really innovative.
- The economical analysers: Morten Gylling and Søren Petersen for analysing lots of different RCG production scenarios.
- The bio-fuel combustion researchers: Juha Huotari, Veli-Pekka Heiskanen, Heikki Oravainen and Susanne Paulrud for finding ways to produce energy from the leaf fraction of RCG.

I wish to thank all involved in the full-scale RCG pulping trial: Lennart Vikström, Carina Sandström, Karina Wiklund, Eva Skoglund, Lennart Nordström, Nils-Åke Johansson, Martti Kojo, Jonas Wiklund and Bo Westerlund. I also want to thank Kjell Wilhelmsson and Bo Ahlqvist for their interest in this project.

Financial support from the European Commission (Project AIR3-CT94-2465), Kempe Foundations, Stiftelsen Lantbruksforskning and the Swedish University of Agricultural Sciences is gratefully acknowledged.

Finally, many thanks to my wife Gunilla and my kids Malin, Amanda and Olivia for their patience during the final preparation of this theseis.

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