MAFF FUNDED R&D PROJECT NF303

THE INDUSTRIAL POTENTIAL OF FIBRE FROM UK – GROWN CROPS

SCIENTIFIC REPORT

1. Objectives and background

The overall objective was to assess the potential feasibility for industrial use of fibre from twelve crops suitable for growing in the UK. The applications investigated were pulp and paper, wood-based panels, and textiles. The 10 scientific objectives and 26 milestones, as set out in the CSG7 form for the project, are annexed to this document.

The research was carried out by five organisations, each of which presents its final project report as a separately bound annex to this consolidated report:- ADAS (Annex 1), the Agricultural Research Institute of Northern Ireland (Annex 2), the BioComposites Centre University of Wales (Annex 3), Silsoe Research Institute (Annexes 4a, 4b and 4c) and the University of Leeds School of Textile Industries (Annex 5). The project was coordinated by Silsoe Research Institute.

The concept of the project was to highlight the potential of the twelve fibre crops by

assessing the costs and feasibility of growing, harvesting and storing the crops, and processing to extract fibre or produce particles from the harvested material,

investigating the properties and processability of the extracted fibre or particles for the end uses of pulp and paper, wood-based panels and textiles, and investigating the properties of the prototype products made,

assessing the economic competitiveness, both of the fibre crop against other crops on the farm, and of the fibre and particles against competing materials in industrial markets, and

investigating the industrial acceptability of the fibre materials and prototype products.

2 Research carried out and results obtained

The research is described by objective with the responsible organisation indicated.

2.1 Growing of crops (ADAS)

Crops of hemp, reed canary grass, flax, miscanthus, nettles, annual and biennial hollyhocks, marshmallow, milkweed, *Asclepias syrica*, linseed, wheat, oilseed rape, *Kitabella vitafolia* and *Malva sylvestris* were grown by ADAS at sites in southern England during 1995-1997. The crops were harvested, field dried and retted as required, then material from these crops and woodchips of poplar coppice was passed on to Silsoe Research Institute (SRI) for fibre extraction and processing. Frozen samples of each crop were also passed on for determination of equilibrium moisture content. Records of crop management, crop production, dry matter content of harvested crop material and weather conditions during each growing season were kept and used in the economic analysis of crop production by SRI.

Hemp, reed canary grass, miscanthus, flax, wheat, oilseed rape and linseed all produced good yields of straw suitable for fibre extraction and could be grown using equipment and skills normally available to arable / grassland farmers. Fibre material was produced from the other crops grown. However, crop production problems were encountered due to poor crop establishment, low yields, the lack of effective herbicides approved for use and the requirement for specialist horticultural equipment or high labour inputs. Milkweed and *Asclepias syrica* had poor winter hardiness. Further agronomic research would be needed to ensure consistent production of material suitable for fibre extraction from these novel crops under normal farming conditions in the UK.

2.2 Harvesting, drying and storage (Silsoe Research Institute)

2.2.1 Harvesting

Two aspects of harvesting are reported on in Annex 3a; harvesting of the samples grown and used within the project for fibre, and the feasibility of harvesting such crops in commercial practice. Here, the harvesting feasibility is summarised, together with some concerns.

If a new crop is to be grown, the ideal from the grower's viewpoint is that the crop is harvestable using equipment already available on the farm. Assuming a combine harvester, forage harvester and round baler come into this category, then a conclusion of the harvesting study is that it is physically possible to cut all the crops using existing farm equipment.

The problems that arise are related to four factors; the strength of the fibre, the need for correct retting for extraction of long fibre, the requirement to harvest in late winter or early spring, and the requirement for drying. These are dealt with in turn.

Fibre strength. For the crops containing strong bast fibre (hemp, linseed, flax and nettle) the cutting device must be in excellent mechanical condition, with well-adjusted clearances and with adequate power. It was feasible to mow or swath green hemp, and to cut desiccated flax and linseed with a combine harvester, though the crop density imposed a limit. Nettle was judged to be no more difficult to cut than hemp.

Retting. Bast fibre crops (hemp, linseed, flax, nettle, hollyhock, marshmallow) require retting before extraction of long fibre is possible. If the crop is grown for particles, retting is not needed. Under or over retting reduces the value of the fibre, so getting the retting correct is important to the grower. If the weather is damp when the crop is at the correct stage of retting, the crop cannot be baled because deterioration would continue. In the absence of a means of drying the crop artificially, the crop may be lost.

Harvest in winter. Crops harvested in late winter or early spring (Miscanthus and reed canary grass) pose two harvest problems, the likelihood of soft wet ground for the machinery (this also applies to coppice), and the likelihood that the harvested material is too damp for storage. Continental conditions of frozen ground and cold-desiccated crop are unlikely in UK conditions.

When considering feasibility, harvesting must be considered as a part of the overall system. Chopping the crop at the point of harvest may be rapid and produce a material suitable for bulk handling but if the drying of the particles cannot realistically be achieved, the system is not feasible.

The approach taken to investigate harvesting feasibility in commercial practice was as follows. First, the literature was surveyed to determine the extent of information available on systems and performance measures such as workrate. Second, a number of telephone interviews were carried out with machinery company technical staff, users of machinery, including crop producers and contractors, and with companies involved in harvesting. Third, where shown necessary, measurements were made of workrate of machinery operating in commercial crops.

For wheat straw, oilseed rape and linseed, harvesting is straightforward and workrates are available. Linseed must have been adequately desiccated.

The system of flax harvesting used by producers for the apparel textile industry involve a low rate, high cost method of pulling, turning during retting and baling of aligned straw to maximise quality. This method is not appropriate for fibre destined for industrial applications because of cost. The combine harvester has been used successfully to harvest flax, provided the crop is sufficiently well desiccated and not too dense.

Hemp for use as a source of particles or short fibre for pulping could be cut and chopped by a forage harvester. Because of the strength, toughness and flexibility of hemp stems, it is essential that the cutting device is in good mechanical condition, with well-adjusted clearances and with adequate power because mowing of hemp imposes higher demands on the machine than does mowing of herbage. Particles can be ensiled with a chemical preservative to avoid drying but Dutch experience suggests fibre quality is reduced during storage. For hemp long fibre, cutting by mowing would be followed by retting for 2 - 3 weeks in the swath. Turning of the swath would be required to produce even retting.

Miscanthus and reed canary grass. A self-propelled forage harvester fitted with a Kemper-type header can cut and chop these crops and blow them into a trailer for transport to the store. Further drying if required could be attempted in a silo, in a stack covered by plastic sheet or in a grain floor store. The effectiveness of these systems is not known. Handling and transportation would be as a bulk material, though the material could, if chopped particles were sufficiently long, be baled for more economical transportation This system is not suitable if the standing crop is too moist for direct storage and if drying is too expensive or not available. An alternative harvest system would then be to mow the crop, collect and load into a trailer with a tractor-mounted loader. During storage under cover the crop would be expected to dry to some extent because of the open structure of the sticks in bulk but no estimates of the likely drying rate are available. It could be transported in bulk as sticks, baled as sticks, or chopped.

Nettle, marshmallow and hollyhock. For long fibre, these pose similar problems to hemp.

Milkweed. A harvesting system for the seed heads is not available, but this is irrelevant because the crop proved unsuitable for UK climate.

2.2.2 Drying and storage

Even for crops harvested in late summer or early autumn, the weather can be sufficiently wet that drying may be required, and the later in the season the harvest is carried out, the more unlikely is weather with good drying potential. As noted above, crops harvested in winter or that require to be damp for retting to occur also impose drying needs. Drying was outside the scope of the project but conditions for mould-free storage were studied.

The primary objective of this work was to determine the equilibrium between the moisture content of the fibre and the partial vapour pressure of the water in the surrounding air. The equilibrium relative humidity (or water activity) has significance in defining storage norms, e.g. fungal activity is negligible at relative humidities $< 65\%$, and is of fundamental importance in the computation of drying in deep beds.

The method of determination involved a small sample of fibre held in a sealed container in which the temperature was controlled and the relative humidity determined at equilibrium. The equilibrium moisture content of six of the fibre species was determined using between four and seven values of moisture content. The determination was repeated for different temperatures of the fibre. The data were fitted to four equations often used to describe the equilibrium relationships between moisture content, air temperature and relative humidity. There was no material available for measurement of equilibrium moisture content tests on Milkweed, Marshmallow and Hollyhock.

A secondary objective of this work was to determine the effect on the estimated moisture content of the oven temperature used in its determination. At SRI, moisture content of biological material has been determined by oven drying to a constant mass at a temperature of $105^{o}C$. It emerged that some collaborators were using an oven temperature of 80 ^{o}C. Since moisture content was likely to be a defining factor in any comparison of results between collaborators, an experiment was conducted in which samples of eight fibre crops were dried to constant weight at a succession of increasing temperatures.

2.3 Fibre extraction (Silsoe Research Institute)

Fibre for textile use requires that the crop be prepared by retting to weaken the bonds between the fibre and the core. Then the long, bast fibres can be extracted by decortication using the equipment developed at Silsoe. If the stems are under-retted the fibre remains strong but many particles of the woody core remain attached to it. Over-retting causes the long fibre itself to be weakened so that it breaks during processing and its value for textile use is severely reduced.

Producing fibre for pulping and board from crop containing long fibre requires no retting; indeed retting is undesirable, not only because it removes some of the plant components that might affect board properties, but also because the long fibre must be cut into short pieces to avoid problems in the pulper. Attempts to cut retted stems tend to release long fibre, which wraps in the cutting equipment. Therefore stems for pulping and board making were required to be unretted or at least under-retted - it is not always possible to avoid any exposure to moisture in field.

Three processing routes were established, for textile applications, for pulp and for particle board For textile applications, straw was retted. For flax, hemp and linseed this was done in-field. For the other long fibre crops, nettle, marshmallow and hollyhock, retting was done under controlled conditions in a water bath. Retted, dried crop was then processed through the Silsoe laboratory-scale decortcator to separate fibre from non-fibre parts of the stem. For pulping, the stems were passed through a slicer developed at Silsoe, comprising a bank of rotating sharp-edged discs, to reduce the length to a nominal 20 mm, or passed through a forage harvester. For particle board, the sliced material was further processed by hammer milling to give a particle size determined by the size of the holes in the mill screen.

2.4 Fibre quality of UK flax and linseed (ARINI)

The aim of this aspect of the work was to compare the quality of UK produced fibre from flax and linseed crops with that being used by industry. The strategy was to obtain fibre samples representing crops of linseed and flax within the UK and to compare these with samples of fibre representing that being traded in the European Market. In order to evaluate more precisely where the differences arise from between samples a replicated experiment was carried out in Northern Ireland.

Samples of fibre produced from UK crops of flax, linseed and hemp were collected along with samples representing high and medium quality flax and jute of the types being processed, or capable of being processed within the UK. The UK samples were either from commercial flax crops which had been grown in Northern Ireland, pulled retted and scutched in the traditional manner for the production on long fibre or had been grown in England for combine harvesting and decortication. In addition a field experiment was carried out in Northern Ireland in which a flax and a linseed variety were each grown at low, medium and high seed rates. At maturity, part of each plot was pulled and dew retted, part pulled and water retted, part pulled and dried and part sprayed with 'Touchdown' as a standing crop which was then allowed to desiccate and ret before being pulled about 6 weeks later. Fibre was extracted from samples of straw from each of these treatments by scutching and hackling. In addition samples of straw from the medium seed rate were also decorticated at Silsoe Research Institute and fibre samples obtained.

Each of the fibre samples was subjected to a range and chemical and physical analyses including fibre length, fineness, freedom from impurities, pectin and lignin contents, crude fibre and tests for the degree of retting. In addition fibre length distributions and shive (impurity) weights were determined on a selected range of samples so that the effects of decortication could be compared directly with the effects of scutching and hackling.

Method of production. The results of the fibre analyses carried out reveal the very wide range of fibre qualities which can be produced from UK fibre crops. When flax crops are grown, harvested, retted and scutched in the traditional manner for the production of long fibre then clean fibre, free from shive, can be produced with fibre length and fineness qualities very similar to that of the best Belgian water retted flax. On the other hand, when grown, harvested and decorticated in the manner of most of the English crops included in this study, ie low seed rate crops desiccated and combine harvested, short fibre is produced which is not only shorter than the tow fraction from traditional flax, but also contains a high level of woody shive, from 15% to over 50%.

Linseed vs. flax. When linseed as opposed to flax crops are considered there are a range of differences which are of importance. Linseed straw is less easily retted than flax straw and after extraction a higher proportion of shive can be expected. The clean fibre yield is only about 50% that of flax managed under the same conditions and the fibre is shorter and more lignified.

Fibre extraction. Irrespective of what form of straw entered the decorticator, retted or unretted, the fibre extracted was predominantly in the 5 cm to 20 cm length range. The proportion of shive did vary with the retting in that there was a higher amount of shive amongst the fibre of the unretted samples. However the overall yield of clean fibre from decortication was very similar to that from scutching so that as a method of extraction there do not seem to be significant losses during the process.

Retting. Differences in the chemical analyses could mostly be related to the degree of retting which the crop had received Pectin and lignin were low in well retted samples and ether extract and crude fibre measures were higher. Of the two boiling tests water boiling seemed to be a better indicator of retting, although it is the caustic boiling test which has been most widely used for this purpose in the past.

2.5 Processing for pulp and paper (The BioComposites Centre)

Fibre length
The cell lengths of samples of the crop materials were determined using two complimentary approaches. For each material, the mean length of fibres alone (from the sclerenchyma tissue) was determined using light microscopy. In addition, the mean overall cell length of samples from each of the materials was also determined using an automated fibre length analyser (Kajaani 200).

Chemical Composition
The chemical composition of samples from each of the crop materials was determined using a sequential method. The method was developed at The BioComposites Centre for analysing wheat straw in the LINK-Crops for Industrial Use Project: Multi-use approach to cereal straw fractionation using thermomechanical pulping. Each material was analysed for the following constituents: lignin, α-cellulose, hemi-cellulose, chloroform / methanol solubles (wax), protein, hot water solubles, pectin, ethanol solubles, ash and silica.

Mechanical Pulping
Samples of each crop material were pulped using an atmospheric disc refiner, using a schedule optimised for the reference material (spruce). Pulps were screened to remove shives, and attempts made to produce handsheets from the pulps for evaluation of properties.

Pulps produced from all the crop materials studied were characterised by having a very low fibre length and poor drainability. As such, it was impossible to form handsheets using the standard methodology, and hence evaluation of pulp properties was not possible.

Semi-chemical Pulping

Samples of each crop material were cooked using a standard Neutral Sulphite Semi-Chemical (NSSC) pulping schedule. The standard schedule used was that developed for cooking mixed hardwoods (the reference material), which in turn was based on that used by the St Regis semi-chemical pulping mill sited at Sudbrook in South Wales. For each crop material, the oven dry (OD) yield of material obtained from the standard NSSC cooking schedule was determined; a number of additional cooks were then carried out at varying maximum temperatures, to determine the optimum cooking temperature for achieving an OD yield of between 76% and 77%. After cooking to achieve optimised yields, material was defibrated in a disc refiner. The resultant pulp was then beaten, handsheets made, and the pulp properties evaluated. Results for each crop material were compared with those obtained for the mixed hardwood reference pulp.

All crop materials required lower cooking temperatures than the mixed hardwood reference material to give yields of around 76%. However, all pulps were characterised by having relatively poor drainage properties. Pulp properties were generally inferior to those of the hardwood reference pulp. In particular, the stiffness properties were significantly lower. An exception to this general trend were the long fibre crop materials e.g. hemp, flax, linseed and nettle, which produced pulps with markedly superior tear properties. It was shown that by pulping to yields of around 70% that pulp properties could be improved, though the stiffness properties of the pulps were still significantly poorer than those of the hardwood reference pulp. Miscanthus, reed canary grass, wheat and rape straw were the most promising in terms of overall pulp properties of the crop materials evaluated.

Chemical Pulping

Samples of each crop material were initially cooked using standard Soda/Anthraqinnone (Soda/AQ) pulping conditions. The standard cooking conditions used were those developed and optimised for pulping Eucalyptus (the hardwood reference material). The yield of screened fibre obtained from the standard pulping conditions was determined. A number of additional Soda/AQ cooks were then carried out for each crop material, using cooking liquors of varying active alkali content, in order to determine optimum cooking conditions for maximising the yield of screened fibre. Handsheets were made from the highest yielding pulps and their properties evaluated. Results for each crop material were compared with those obtained for softwood (Spruce) and hardwood (Eucalyptus) reference materials.

The highest yields of pulp were achieved with miscanthus, which exceeded those of spruce and were equivalent to those of eucalyptus. Wheat straw, reed canary grass and coppice poplar gave similar pulp yields, being some 20% lower than for eucalyptus, and slightly lower than typical yields for spruce. The long fibre crop materials were generally characterised by having high chemical demands and low pulp yields i.e. less than 40%.

In terms of physical pulp properties, miscanthus pulps compared very favourably with those of Eucalyptus Kraft pulp; the tensile and burst properties of miscanthus pulps were lower than those of spruce Kraft pulps. In terms of overall properties, pulps derived from wheat straw and reed canary grass were the most promising of the other crop materials evaluated. Pulps derived from the long fibre crops exhibited very high tear properties and high brightness.

2.6 Processing for wood-based panels (The BioComposites Centre)

Particleboard
Chopped, hammer-milled furnish from each crop material was sieved over meshes with 5 and 1mm apertures to remove over and undersized particles. Boards were made comprising 100% of each the crop material, and 20% of the crop material and 80% of a standard industrial wood chip furnish. Two resin systems were evaluated: urea formaldehyde (UF) and isocyanate (MDI). Wax was also added to all boards. Material was hot-pressed for 3 minutes to form 12mm thick boards using platen temperatures of 165^{o}C. The bending, internal bond strength and thickness swelling properties of boards were evaluated and compared with those obtained for control boards made from industrial wood chip furnish and the two resin systems. In addition to the originally scheduled work some additional studies were also undertaken with rape straw and reed canary grass to determine the effect of wax addition and particle size on board properties.

Particleboard test panels made from both 20% and 100% coppice poplar and UF resin had strength properties which were equivalent to those of panels made from wood alone. However, the thickness swelling properties of boards containing coppice were slightly inferior. Other crop materials that showed promise as raw materials for UF-bonded particleboard, at least at low (20%) wood substitution levels, included nettle, hollyhock and marshmallow. The shiv material of both nettle and hollyhock appeared to be better suited as raw materials than the whole stem material. The properties of UF-bonded boards made with other crop materials were significantly reduced, even at wood substitution levels of 20%; in particular, the internal bond strength and resistance to thickness swelling properties were significantly reduced. UF-bonded panels could not be produced from either wheat straw or reed canary grass alone using standard processing conditions. Improvements in the properties of panels made from the less promising crop materials were realised by using MDI resin. However, the properties of panels were still significantly worse than those of UF-bonded wood particleboards. In some additional studies it was demonstrated that the properties of MDI-bonded reed canary grass panels could be improved by not including any additional wax in the furnish. From additional studies on rape straw, it was also evident that board density and particle size were important variables in determining panel properties; pressing to higher densities and the use of smaller particle sizes gave improvements in panel properties.

Medium density fibreboard (MDF)
For each crop material, boards were made comprising 100% of the crop material, and 20% of the crop material and 80% softwood spruce chips. Chopped materials, either alone or pre-mixed with wood chips, were fed continuously into a digestor. The material was defibrated in a pressurised disc refiner, blowline blended with UF resin and wax, flash dried and hot pressed at 170^{o}C for 3 minutes to form 12mm thick boards. The bending, internal bond strength and thickness swelling properties of boards were evaluated and compared with those obtained for reference boards made from softwood spruce chips.

At wood substitution levels of 20% all the crop materials evaluated showed promise as raw materials for UF-bonded MDF. In many cases, in comparison with panels made from spruce alone, panel properties were not significantly reduced. The most significant reductions in internal bond strength were observed in panels containing coppice poplar and reed canary grass. Thickness swelling properties were either unaffected by the inclusion of the various crop materials, or even improved in the case of wheat straw and coppice poplar. When attempts were made to process each of the crop materials alone, using standard process conditions, panels were only produced comprised of coppice poplar, miscanthus, rape straw and reed canary grass. The physical properties of these panels were significantly worse than those of panels made from spruce alone; panels made from coppice poplar had
the most promising properties. In the case of wheat straw, it was possible to produce fibre blended with resin. However, attempts to press panels from this furnish proved unsuccessful. The long fibre crop materials proved to be very difficult to process; considerable difficulties were experienced in feeding the materials into the refiner.

2.7 Processing for textiles (University of Leeds School of Textile Industries)

2.7.1 Raw fibre cleaning

Mechanical cleaning of basic decorticated fibre

It is clear from discussions with potential users of flax and hemp fibre that one of the main considerations limiting acceptability of the fibre is the lack of 'cleanliness' i.e. the presence of dust and shiv (stalk fragments). A further consideration is the variability in fibre characteristics observed even within a sample. There are no means, at present, of quantifying fibre quality objectively and hence evaluating this parameter. A range of techniques for mechanical separation of fibre from trash used in the cotton industry have been applied to flax fibre (the closest to cotton in characteristics) but these have not been successful in effecting a complete separation. In order to obtain quantities of fibre for the fabrication of test pieces of fabrics, a Shirley analyser was set up specifically to maximise the yield of relatively clean flax and quantities of fibre were produced.

The cleaning of fibre by mechanical means, using existing textile equipment is the only economically feasible route for the production of acceptable fibre. The greatest disincentive to the acceptability of UK sourced fibres to potential users is the presence of both free shiv and, in particular, shiv attached to fibre. The presence of this adversely affects the use of carding and similar equipment. The shiv contaminates the wire of the card, and although this can be tolerated in the manufacture of test samples of fabrics, a commercial operation would not be feasible. The use of needling equipment is also limited by the presence of shiv, this causes needle breakage where fine needles are used. Fabric with better appearance and characteristics was possible where a sample of mechanically cleaned fibre was processed with a needle loom.

Fibre wet processing

Investigations have shown that fibre scouring and bleaching is successful in reducing the shiv and dust content of the basic decorticated fibre. This removal is mostly of free shiv, not that attached to fibre. The resulting fibre is, however, extremely tangled and requires working to produce a material suitable for further processing. An economic evaluation of the effectiveness of cleaning fibre commercially by this route would be necessary to assess the effectiveness of this process route. The technical feasibility of bleaching the fibre using commercial plant and laboratory scale tests has been carried out. The bleached fibre is more acceptable to some potential end users, but they all appear to be operating in highly price sensitive environment. The bleaching process produces irreversible chemical change to the fibre surface chemistry and also a degree of fibre bundle separation into ultimates.

Microbiological assessment of the activity associated with bast fibres and dust
Historically there has been an association between working with bast fibres and lung disease (Byssinosis). This association is thought to be due to microbial activity arising from the retting process. Concerns about the commercial implications of a high level of microbial activity associated with processing dust and fibres have meant that this aspect of bast fibre processing should be addressed in this project. A range of fibres and associated process dusts have been examined for microbial activity by extracting into aqueous solution for 15 minutes, plating and incubating for 3 days and carrying out a total colony count. Samples of flax, hemp, marshmallow, hollyhocks, nettles and milkweed floss (a seed hair, not a bast fibre) were examined in this way. Cotton was assessed as a positive control and polypropylene used as a blank to illustrate the integrity of the system. All the samples showed substantial activity when assessed in this way, in all cases being greater than cotton. There was little difference between the counts measured for dust and for fibres from the same sample. Bleaching the fibre reduced the counts, but did not remove microbial activity. It is clear that both fibre and the associated process dust have substantial microbial populations.

2.7.2. Fibre blending

Blends with cotton
Flax and hemp processing down a cotton-processing route has proved unsuccessful where the fibre is not blended with cotton. Hemp in particular is unsuitable for this process route, being too coarse and brittle. Test yarns of 50 : 50 cotton flax blends have been successfully produced by open end spinning and ring spinning. These yarns are not fine enough for apparel applications, a potential use is in commercial matting or carpet.

Blends with polypropylene
Blends of flax fibre and polypropylene were prepared. These incorporate different fineness grades of polypropylene. The blending was done using small laboratory scale opening equipment with the basic material being rag pulled flax fibre (single pass). The blends were prepared and subsequently processed using rag pulling equipment to produce a 'bat' that was needled and callendered. Microscopic examination of the callendered fabric showed obvious physical changes, the polypropylene fibre having melted at the callendered surface and acted to some extent as a binder. A crude fabric faced with polypropylene was produced. Non-woven fabrics with better blends of flax / polypropylene made by needling have been produced. These show the blending to be uniform. When heat-treated the polypropylene melted and acted as a binder in the fabric.

Knitted fabrics made up from flax / cotton yarns incorporating a thermoplastic component (polypropylene) at 15 - 50 % were heat treated at 180-205^{o}C with pressure being applied. Examination of the samples indicated that at suitable pressures and temperatures the polymer flowed to wet the yarn. Under these conditions the thermoplastic component enabled the knitted structure to be formed into a self-supporting structure. These structures have applications as technical textiles, being used as preforms in the construction of interior panel for the automotive industry.

Blends with wool

Initially, a blend of 70% flax fibre and 30% wool was prepared using rag pulled flax fibre and wool. This was mixed by hand prior to processing. It was noticeable that an amount of loose shiv was present in the flax fibre even after rag pulling. The wool / flax blend was processed to produce a sliver, it appeared that flax alone could not be formed into a sliver. The potential of this blending was investigated in further trials.

In the first trial, blends of 100:0 wool : flax, 75:25 wool : flax, 50:50 wool : flax, and 0:100 wool : flax were made up. These were made from a relatively cheap short length wool and flax fibre cleaned by processing through a Shirley analyser to remove shive and short fibre. Both bleached flax and unbleached flax were used, i.e. a total of 9 blends in all. All the blends were successfully processed to produce a carded sliver. In both cases the flax fibre without wool would not hold together to form a sliver. The blend slivers produced were subsequently processed on a laboratory scale woolen card with condenser to produce a slubbing for spinning. The 100% wool was successfully processed by this route, but all the blends, even 75 : 25 wool flax lacked the structural robustness to be processed by this system. Both standard commercial settings and variations on commercial settings were used in an attempt to produce a yarn, but this was unsuccessful.

A second trial was carried out using a longer, better quality wool in the expectation that this would provide greater structural integrity to the sliver and enable a semi-worsted processing route to be used to produce a yarn. In this trial 100 : 0 wool : flax, 75 : 25 wool : flax and 50 : 50 wool : flax blends were again produced. Slivers with sufficient structural integrity for further processing were successfully produced from all the blends. These were processed by a semi-worsted route through gill boxes and a ring frame spinner to produce a yarn. This was made to a typical hand knitting specification with low twist at nominal 200 tex. Examination of the yarn showed the presence of flax to adversely affect the appearance, regularity and strength compared with a 100% wool yarn.

It was clear during processing that the card was affected by the presence of shiv, even on cleaned samples (after each flax sample the card required cleaning). Observations during processing, particularly through the gill boxes and spinning frame, confirmed that there was significant loss of short fibre during yarn manufacture. The fibre cleaning process used here, without which no processing down this route can take place, shortens the flax fibre such that it is not suitable for blending with wool. It is possible that longer flax fibre may be suitable for blending with wool, but this fibre must be clean and suitable for running down existing process lines. The economic advantage of such blending must be clearly established as there appears to be no enhancement of the properties of a 100% wool yarn by the addition of the flax fibre used in these trials.

Electron microscopy of a flax : wool blend highlighted the difficulties of processing these two diverse materials together. The flax, even when cleaned, bleached and processed has variable fibre dimensions, containing fibre bundles with a range of diameters. The finest flax fibres are comparable with wool in terms of fibre diameter, but are significantly different in conformation and structure.

2.7.3. Fibre Processing into non-woven fabrics

Needle loom fabrics

From previous work it is clear that non-woven fabrics of flax and hemp can be constructed by conventional needling techniques on a needle loom. A range of such materials has been produced with the characteristics of a typical cellulosic non-woven fabric. It is clear that fibre for use even with this robust technique requires further processing after decortication. The basic fibre requires clean-up so that the precursors to needling can be preformed without excessive machine contamination. Dust hazard minimisation is also important as this widely used manufacturing technique produces dust even from a clean fibre. The process of calendering is the application of heat (typically 100-200^{o}C) and pressure (usually in the range 5-50 psi) by a pair of rollers to a fabric. This process is usually applied to synthetic polymer fabrics to produce a smooth finish on one or both sides of the fabric. As the material in contact with the roller is heated under appropriate conditions, it will melt and flow to provide bonding between the individual fibres in the fabric. Flax fabrics and others were calendered in a pilot plant calender roller. The application of heat and pressure to the surface of the non-woven material produced a surface finish. This finish is associated with contact by the heated roller of the calendering equipment rather than purely by the application of heat and pressure. Microscopic examination of the calendered surface revealed that there was a deformation of the flax fibres themselves during the process. The flax fabrics gave a substantially better surface finish than the others, including competing non-UK sourced fibres such as jute. Although there is no explanation for this presently available, it is reasonable to speculate that this is due to the natural oil content of flax, linseed oil as found in flax having particular properties when heat treated. The ability of flax fibre based non-wovens to form this calendered finish without the use of synthetic additives is of interest to the automotive industry. This interest may result in a future project based on the substitution of flax fibre for synthetic fibre in car interior panels. For this to happen, other problems such as degradation and odour when wetted need to be eliminated.

Hydroentanglement

An alternative technology for the production of non-woven fabrics is 'hydroentanglement'. With this technique high pressure jets of water are used to entangle the fibre rather than barbed needles as in the more widely used needle punching technique. These jets are typically produced at 70-120 bar of pressure from nozzles of diameter ~100μm. These are typical settings used in a commercial application. Sample pieces of non-woven fabrics using this equipment have been made from flax, hemp and nettle fibre. Examination of the fabric indicates that a material with a greater degree of fibrillation of the fibre bundles is produced, i.e. the action of the water jet has a different effect to that of the needles in needle punching. This technique offers the possibility of processing finer preformed webs and giving a better fabric finish, thus widening the potential use of flax and related fibres.

2.7.4. Other fibres and areas of activity

The hollyhock and marshmallow fibres were assessed for industrial potential. They are excessively coarse and brittle and cannot be fed down any process route tried without significant fibre breakage.

Investigation into the application of enzymes to these fibres was restricted to the evaluation of the effect of pectinase. This was found to have a more complex action than anticipated, a review of other work in the field indicates that this field of activity is beyond the scope of this project.

Examination of milkweed seed fibre shows that the fibre is hollow and has significantly different surface chemistry to the bast fibres. It is possible that milkweed fibre can be used in some niche markets where hollow fibre is desirable. There was insufficient milkweed fibre produced for the evaluation of possible process routes.

The feasibility of substituting natural fibres for glass fibre in composite materials has also been assessed with test pieces being made. There was substantial loss of strength with the use of natural fibres. This is thought to be due to the surface characteristics of cellulosic fibres, in particular their water sorption properties. If these materials are to be used in this application an investigation into the modification of the surface chemistry of the fibres and the economics of this potential use is necessary.

2.8 Acceptability by industry (ARINI, University of Leeds School of Textile Industries and the BioComposites Centre)

Textile fibre

The technical and related textiles market is substantial in the UK, covering a wide range of potential products from structural non-wovens, through non-apparel uses such as carpets and related products to medical and industrial fabrics. This market, in general, is price sensitive and flexible in terms of price / performance characteristics. There are a number of alternative sources of raw material established as acceptable and it is practice in the industry to utilise a number of these sources at any one time. In general, a variety of materials is used to achieve the desired technical performance rather than relying on a single defined fibre supply. This allows flexibility in fibre sourcing and response to changes in customer specifications. There is interest in decorticated flax and hemp, particularly sourced in the UK, as an addition to this portfolio of raw fibre sources.

Samples of fibre and related products were presented to representative companies in specific industrial sectors for comments and an assessment of the suitability of the fibre. These comments, broadly speaking, reinforced the general considerations above, emphasising both the importance of price competitiveness with existing fibre supplies and the requirement for a reliable measure of quality and cleanliness.

Pulp, paper and wood-based panels

The opinion of industry on the commercial acceptability of the more promising products was sought at conferences and during regular contacts over the course of the project duration.

2.9 Economic assessment (Silsoe Research Institute)

The fibres have been evaluated by the project partners for their technical suitability within the main fibre markets in the UK. This information has helped identify the most likely industrial markets, the prices of any competing fibres and the potential volume that could be supplied to these markets.

If UK agriculture can profitably supply industry with crop derived fibres at competitive prices then the implication is that the business is viable for both parties. Thus, the financial modelling has attempted to establish the minimum market price (given yield & support-payments) at which a rational farmer would grow these fibre crops. Compared with this is the maximum farm gate price at which the industry could afford to buy the crops, calculated from their processing costs and the market price of competing fibres. The results are presented at the 'farm gate' rather than at the 'factory gate' to aid comparability from an agro-business perspective.

In discussion with the project partners, the technical factors limiting the profitability of fibre crops were identified. For each technical factor, a range of levels was identified ranging from current practice to the better level if all technical problems could be solved by research or innovation. Scenarios were defined for every combination of technical factors at a variety of possible levels. Some of the scenarios also include a range of subsidy payments for those crops that are not currently supported. The profitability of each scenario was then calculated to determine the situation necessary for each fibre crop to be viable.

The optimizing Silsoe Whole-farm Model has been used to establish the minimum 'farm-gate' price at which the fibres can be produced. This model is a linear program that optimizes the cropping, techniques and mechanization of a farming system subject to constraints of soil and rainfall. The model is used to create a representative farming system to act as a reference scenario. In turn, each of the fibre crops is deliberately introduced into the reference scenario on the basis that the fibre/ straw is given away. Consequently the profitability of the farm falls. This fall in profitability must be covered by the fibre crop if it is to be successfully introduced into that farming system. To gain a widely based value for the price obtained for the fibre crop this process is repeated for a number of soil types and cropping systems. The costs of storage and drying are carried by the farming sector. These costs occur outside the Silsoe Whole-farm Model and have thus been treated separately.

In order to estimate the maximum price that the processing industry will pay for the fibre a point has to be identified where the fibre is in direct competition with its nearest rival. From this point, allowing for any differences in fibre quality, it is possible to 'back-calculate' using various financial models of transport and processing systems to the 'farm-gate'. However, the quality and quantity of hard financial data on the microeconomics of off-farm operations are often very limited. The financial models have been based on the closest analogous process that we have found data for, such as the SRI-developed flax decorticator rather than the traditional flax scutching process.

3 Conclusions

3.1 Growing of crops (ADAS)

ADAS' work has shown that it is possible to grow a range of crops in Southern England for fibre production. However, not all of the crops are currently suitable for commercial field-crop production. Further research on the agronomic aspects of the crops would be needed to improve production.

It was simplest to obtain fibre material as by-products of the current major crops wheat, oilseed rape and linseed, requiring no additional inputs except for allowing time for field retting if this was needed. It was also simple to grow flax for straw production using similar inputs to spring linseed with conventional arable machinery. Reed canary grass, miscanthus and hemp produced good straw yields when grown on a field-scale using minimal inputs and conventional arable/forage crop machinery, with the exception of the initial establishment of miscanthus which was by hand planting. These crops all look promising for commercial fibre production. The perennial crops reed canary grass and miscanthus, had the advantage of increasing straw production each year after establishment, with only minimal further inputs. However, removal of miscanthus and reed canary grass plants at the end of the production period may be difficult due to the persistence of these plants.

Production of nettles, hollyhocks, marshmallow, milkweed and *Asclepias syrica* on a field-scale was problematic and required high labour input. The main problems were poor crop establishment and weed competition. It was possible to improve production using specialist horticultural equipment, irrigation and hand labour. The most promising of these crops, in terms of crop production, were biennial hollyhocks and nettles which both have the advantage of being perennial crops. The nettles did not produce material suitable for mechanical harvesting until the third season but with improved weed control, harvest should be possible in the second season. Winter survival of *Asclepias incarnata* (milkweed) and *A. syrica* was poor at ADAS Bridgets (Hampshire), indicating that these plants may be unsuitable for growing as field crops in the UK. However, these crops need to be further evaluated before condemning them on the basis of these limited trials. *Asclepias syrica* is grown commercially in Romania where the average daily minimum temperatures during the winter (December to March) are very low compared with ADAS Bridgets. Historically, milkweed has been grown in Lincolnshire where average winter temperatures are lower than at the ADAS sites.

Establishment of nettles, hollyhocks, marshmallow, milkweed and miscanthus was improved by transplanting seedlings or rhizomes, compared with sowing seeds. However, transplanting required specialised horticultural equipment and labour. By transplanting seedlings of biennial hollyhocks it was possible to harvest material in the first season, whereas the sown crop did not produce harvestable material until the second season. As these plants are not currently grown as field crops, seed is not easily available and expensive. Establishment was greatly improved by irrigation and may also be improved by sowing or transplanting earlier in spring.

It should be noted that the crops were mainly grown on just one site in southern England (ADAS Bridgets), therefore the potential geographical range for growing these crops in the UK was not tested. Further evaluation of the crops at different sites in the UK over several seasons would be needed to determine their geographical suitability and reliability of production.

3.2 Harvesting, drying and storage (Silsoe Research Institute)

3.2.1 Harvesting

Harvesting systems that are technically feasible have been identified and specified for each of the fibre crops and for each form of the product from that crop. "Feasible" means that technical means are available to accomplish whatever cutting, swathing, threshing and baling are needed to collect the fibre crop. The economic feasibility of harvesting is considered in Annex 4c.

In all cases except coppice poplar and milkweed, harvesting is possible with existing machinery. But such machinery may be too expensive for a typical grower to own so contractor-based harvesting system would be needed. Although the crop may be harvestable, there are interactions of harvesting with other operations, e.g. the need for drying and storage, transport and the effect of harvest machinery on soil structure and the roots of perennial crops. These interactions are commented upon.

For the straw of wheat, oilseed rape and linseed, harvesting requirements are well understood and the rates achievable are well documented.

For hemp, a feasible harvesting system is operated by contractors for commercial growers but there are problems with crop stems wrapping in cutting and baling machinery.

For flax, a harvest system based on combine harvesting, as operated by growers of flax for decortication in England, is feasible. The continental system, based on pulling, was not considered feasible because of the special machinery that would be required. However, pulling can cope with much heavier yields than can combining, so the potential yield of fibre per hectare is limited in the combining system.

For short rotation coppice poplar, much harvesting work has been carried out and feasible harvesting systems have been developed, though a specialist header would be needed for a forage harvester or a specialist harvester for coppice sticks.

For nettle, hollyhock and marshmallow, cutting and baling were feasible. Field retting was tried on a small scale and results were poor. Retting in water was successful.

For milkweed, no machine to harvest seed hair is available in the UK.

Retting is vital for crops with long fibre. But retting in field is subject to uncontrolled variations because of the weather, and also the damp condition of stems at the correct stage of retting may prevent baling. Hence retting in field is a major source of uncertainty.

3.2.2 Drying and storage

Drying to a moisture content low enough for mould-free storage is a problem for some crops. This is particularly so where a) the optimum agronomic stage for harvest is not in the summer or early autumn, e.g. miscanthus and reed canary grass harvested in late winter, so that the drying potential of the air is poor, or b) where retting is required to release long fibre, because even if the crop is cut in good drying weather, the time and damp conditions required for retting may result in a damp crop at a time when the atmospheric drying potential is low. The work within this project was limited to an investigation of the moisture content that would need to be achieved for storage with low risk of fungal activity. Drying itself was outside the scope of this project.

At an equilibrium relative humidity of 65%, considered to be the requirement for storage without risk of fungal deterioration, the equilibrium moisture contents were typically in the range 13 to 18% (d. b.) at 10 ^{o}C. Miscanthus needs to be the driest for safe storage, with an equilibrium moisture content of 13.1 % at 10 ^{o}C. This compares to the wettest which was linseed with an equilibrium moisture content of 17.6% for safe storage at 10 ^{o}C. The implication is that miscanthus would require more drying than any other fibre crop studied here.

Based on linseed as an example, retting did not influence the equilibrium moisture within the error of measurement.

In general, the Modified Halsey equation accounted for about 95% of the variation for the six fibres in which detailed measurements were made and can therefore be taken as an adequate model in describing relationships between equilibrium moisture content and relative humidity. Coefficients for this equation have been determined so that it can be used in drying and storage studies of the fibre crops.

3.3 Fibre extraction (Silsoe Research Institute)

Fibre extraction covers the production of particles for further processing into particleboard and pulp, as well as the separation of long stem fibres from woody stem material.

It is feasible to chop any of the crops into particles with existing machinery. Such chopping may be used as a means of harvest (if a forage harvester is used) and to make bulk handling of the material possible, but further size reduction and fractionation will be needed for a particular process, e.g. chipboard manufacture. It would not generally be feasible to achieve the chip specification of the processor at the point of harvest.

Processing into fibres or into particles may be carried out at the production site or at the users site. Ease of handling, cost of transport, amount and value of waste and utilisation of machinery are relevant. Also relevant for short fibre crops is any need for drying, because once a crop is chipped drying requires forced (i.e. fan-driven) convection, whereas bulk crop may dry over a limited moisture range by natural convection. Further size reduction from chopped pieces of stem to particles by existing designs of hammer mill is feasible but some separation of fibre and shive (particles of woody core) occurs. This is worst with hemp. Provided the chipped stem is not retted, separation of fibre and shive is not excessive.

Chipping of short rotation coppice poplar is feasible using existing designs of chipper. Chips of freshly harvested coppice always require drying by artificial means to permit storage without fungal decay.

Chopping and hammer-milling of miscanthus and reed canary grass was straightforward. Chopping could be achieved at the point of harvest if the crop needed no further drying.

For flax, linseed and hemp, fibre extraction by decortication is feasible. The decorticator developed for flax and linseed in the LINK Crops for Industrial Use ☺Fibrelin■ project was successfully used for hemp in the present work but hemp imposes greater loads on the machine elements and wrapping was a constant problem. This limits the processing rate because of the need to clean out blockages. Improvements in the decortication of hemp are being tackled in an ongoing EC project, FAIR1 PL95-0396. The content of shives in all decorticated fibres from flax, linseed and hemp is too high for many otherwise feasible applications, so improved processing to reduce the shive content should be a priority.

Once retted in water, nettle, hollyhock and marshmallow can be processed through the laboratory-scale decorticator to give fibre, provided the decorticator rollers are adjusted to grip but not flex the stems . The fibre yield is low compared with flax, linseed and hemp but the plants have not been bred for fibre production. Processing caused no problems although there was too little material available to give much experience.

Milkweed fibre was separated from the seed by hand. Too small a quantity of seed heads was available to attempt any mechanised separation.

3.4 Fibre quality of UK flax and linseed (ARINI)

The quality of fibre produced is almost entirely a reflection of the management of the crop and the methods adopted for harvesting, and retting the straw and extracting the fibre. When grown, harvested and water retted as a fibre crop in NI, the quality of flax fibre after scutching is equivalent to that of high quality Belgian flax while fibre from stand retted and dew retted flax is similar in quality to Russian dew retted fibre.

Techniques for growing the crop, retting the straw and extracting the fibre are available to meet a range of fibre quality standards and could be put into practice if the market was there and the economics were right. The main weakness seems to be in the inability of the decortication process to separate shive from fibre. This is likely to have the effect to making the fibre unsuitable for a wide range of potential markets that require fibre more or less free from shive. The very high proportion of shive in the English farm crop decorticated samples, together with the high lignin content and weight loss during caustic boiling, would suggest that the straw was also poorly retted which would have added to the difficulties of the decortication process.

The relatively short staple length after decortication may not be a problem for those markets for which the fibre would have to be cut to shorter lengths anyway, such as for non-woven materials.

3.5 Processing for pulp and paper (The BioComposites Centre)

Mechanical pulping

The fact that none of the crop materials investigated appeared to be suitable as raw materials for mechanical pulping can be attributed in part to their fibre length characteristics, which were generally significantly shorter than softwoods. Mechanical pulping has a tendency to severely shorten fibres; as such, the pulps produced from the crop materials had fibre lengths which were too short to allow successful handsheet manufacture. The results of this study suggest that significantly different processing technologies would need to be developed in order for crop materials to become viable as raw materials for the mechanical pulping industry.

Semi-chemical pulping

The results obtained from the semi-chemical pulping studies suggest that crop materials such as wheat straw, reed canary grass and miscanthus might be viable as raw materials, providing they were available at a significantly lower cost than hardwoods. However, given that the packaging sector of the paper industry is now almost exclusively geared towards the utilisation of waste paper, it is unlikely that any manufacturer would consider investing in processing plant to produce semi-chemical pulps from crop materials, at least for the foreseeable future.

Chemical pulping

It is evident that chemical pulps made from miscanthus, reed canary grass and wheat straw have properties that would be acceptable in the paper industry. The yields that can be obtained from miscanthus would also make this crop material in particular attractive. However, the investment costs required to establish conventional chemical pulping plants are huge due to the economies of scale associated with the effluent recovery and treatment process. It is unlikely that any such investment would be made in order to process crop materials, particularly given that such plants would have a raw material demand upwards of one million tonnes per annum. Owing to these investment costs and raw material requirements, chemical pulping of crop materials is only likely to become a reality if economically viable smaller scale pulping processes can be developed. The results of the study also confirmed that the long fibre crop materials are suitable for the production of speciality pulps where high tear strengths and pulp brightness are important properties. However, the high chemical consumption and low yields that were obtained suggest that pulping separated bast fibre would be preferable, as opposed to the whole stem as used in this study.

3.6 Processing for wood-based panels (The BioComposites Centre)

Particleboard

From the results of the particleboard studies it is evident that coppice poplar is the most promising of the crop materials investigated. The modest reduction in resistance to thickness swelling that was apparent with the material may be attributable, at least in part, to the methods used to prepare particles and their subsequent geometry. This could be addressed by using more appropriate processing technology. The results obtained from the particle size studies with rape straw would also suggest that both particle size and geometry could be important for other crop materials, and that if these issues were addressed at least some of the materials might show more promise as raw materials for particleboard.

Medium density fibreboard

The results of the MDF studies suggest that all of the crop materials studied could be viable as raw materials for UF-bonded MDF, at least at low levels of wood substitution. Coppice poplar, miscanthus, rape straw and reed canary grass could also be viable at higher levels of wood substitution e.g. up to 50%. Although MDF manufacturers expressed concern over the colour changes in the product, this could in fact be used to their advantage with inventive market strategies. The concerns over longer term effects on the process could be addressed by more extensive and longer term trials.

3.7 Processing for textiles (University of Leeds School of Textile Industries)

In these conclusions, fibre extracted from UK plants by decortication is referred to as fibre for brevity:-

The variable nature of the fibre and its high shiv content severely limit the acceptance of this material by potential end users.

There is a high dust content associated with most of the bast fibres, this has significant microbial activity which may place constraints upon the use of the material in a commercial environment.

Flax and hemp are the fibre sources with greatest industrial potential. Nettle fibre, although difficult to cultivate and extract, is useable.

Flax fibre can be processed down mainstream apparel fibre processing routes as a blend, but would appear to offer no performance advantage over cotton or wool.

Hemp fibre is not suitable for processing by traditional textile processing equipment, and is inherently unsuitable for use as a mainstream apparel fibre.

Hollyhock and marshmallow fibres are not suitable for processing down any route tried.

If the limitations imposed by fibre variability and lack of cleanliness can be overcome, flax and hemp fibre would be acceptable to manufacturers in the technical textiles sector, particularly in the geotextile, horticultural and automotive industries

There is a potential niche market for fibres as surface-active filters for the removal of metals from contaminated water. The metal sorption properties of these fibres have been evaluated, but none of the fibres appears to offer a performance advantage over competing materials. It is, however, possible that a wider study may identify a unique property possessed by one or more of these fibres. Without the specific investigation of potential applications, it is not possible to predict the performance of these fibres. One specific application where funding support is being sought to support further investigations is the use of these fibres for the remediation of acid mine drainage pollution of water.

The fibres have shown to be suitable for thermal conversion into activated carbon fibres. These findings have been the basis of a successful funding application to investigate the formation and properties of activated carbon fibres and their use in air filtration.

3.8 Acceptability by industry (ARINI, University of Leeds School of Textile Industries and the BioComposites Centre)

(Leeds) As a part of the programme of this project, samples of fibre produced by Silsoe Research Institute have been presented to prospective industrial users both as raw fibre and in modified form. The acceptability of this fibre to potential users was explored in discussions. It is clear that, as indicated in the economic modelling information supplied to Silsoe Research Institute, the identified market potential is in technical and related textiles. It was made clear by all potential users that there was a general interest in a UK-sourced material for strategic planning reasons, i.e. security of supply and possible marketing advantage. However, this market sector is extremely price sensitive and fibre supply requires to be competitive with existing materials. There is only interest in flax and hemp as candidate fibres because the others are not available in quantities of interest to industrial companies. There may be possible uses for fibres such as marshmallow and hollyhock, but these are likely to be in niche markets, if at all.

Discussions have clearly delineated two factors which presently limit the use of decorticated fibre, the variable nature of the fibre associated with the absence of a reliable quality measurement, and the amount of shiv and dust present in the basic material. It is clear from our discussions that the fibre as supplied from the Silsoe Research Institute laboratory-scale decorticator is not in general of acceptable quality to industrial users for these two reasons. If the limitations imposed by fibre variability and lack of cleanliness can be overcome, flax and hemp fibre would be acceptable to manufacturers in the technical textiles sector, particularly in the geotextile, horticultural and automotive industries

(ARINI) The inability of the decortication process to separate shive from fibre is likely to have the effect of making the fibre unsuitable for a wide range of markets that require fibre more or less free from shive. The relatively short staple length after decortication may not be a problem for those markets for which the fibre would have to be cut to shorter lengths anyway, such as for non-woven materials.

Acceptability by specific industries

(The BioComposites Centre) Particleboard manufacturers stated that any alternative raw material which fitted easily into their process and gave panel properties equivalent to or better than their existing raw material intake would be seriously considered, providing such materials could compete on a supply price basis. As such, coppice poplar would be an acceptable raw material option if it could be made available at a competitive price.

MDF manufacturers, whilst acknowledging that many of the crop materials appeared to give panels with acceptable properties, expressed some concern over the darker colour of many of the test panels (colour is used as a key indicator of panel quality by many consumers and end-users). Concern was also expressed over the potential long-term effects on the production process of utilising alternative raw materials. Issues that were raised included: build up of silica deposits; increased wear; increased effluent discharged from the process. Despite these concerns however, manufacturers conceded that alternative materials would be seriously considered if there was potential for savings in overall production costs, and providing guarantees could be given with respect to the security of long term supply.

Pulp merchants and manufacturers of printing and writing papers indicated that chemical pulps made from wheat straw, reed canary grass and miscanthus would be acceptable, and would have a place in the market, providing these were available at competitive prices. Producers of speciality pulps derived from chemically pulped long fibre crops e.g. flax, hemp etc. indicated that the most important criterion was cleanliness of the fibre i.e. shiv content. Manufacturers of packaging papers and paper board showed little interest in semi-chemical pulps. The whole industry is now geared to the utilisation of waste paper. As such the industry would not be interested in establishing pulping plants to process the crop materials, and would only consider utilising the pulp if it was available at prices which were competitive with those of waste paper.

Specialist papermakers and beverage related products manufacturers
(Leeds) Samples of basic flax and hemp were presented, and assessed as being unsuitable for use. Further samples of bleached and unbleached carded flax and hemp were subsequently prepared and also assessed for suitability. The bleached and unbleached carded flax and a sample of cleaned cut flax were assessed as possible suitable raw materials. Further quantities of this material have been supplied to the company for testing on their production plant.

Automotive industry component manufacturers
Samples of flax and hemp basic fibre were presented to automotive component manufacturers for assessment as a raw material for car interior structural panels. The basic raw material as presented was assessed as too variable in quality, but there is no technical reason why a more consistent material would not be useable. This sector of the market is particularly price sensitive, but for environmental reasons would be keen to utilise flax or hemp. Samples of calendered flax non-woven fabric were presented both as pure flax and as flax / polypropylene blends. These were of interest due to the finish and increased strength produced by calendering. There are technical problems with dust and with odour when wet which would have to be overcome for this use, but it is believed that natural fibres will provide a better 'comfort environment' in a car interior compared with synthetic alternatives. An application for funding to support further work in this field is being prepared and will be submitted under the Sector Challenge initiative.

Furniture and upholstery manufacturers
Flax fibre is technically acceptable for use in mattress construction and related uses, but the dust content of the basic fibre is a limiting factor

Disposable sanitary product manufacturers
Interest has been expressed in the use of flax fibre in disposable nappies for a specialist market sector. For this use the material must be completely free of shiv. Cleaned and carded flax fibre may be acceptable for this use.

Industrial mats and related product manufacturers
Interest has been expressed by industrial matting manufacturers wishing to improve their environmental awareness profile. Samples of flax / cotton yarns were submitted for assessment of suitability. Following this, quantities of yarn were manufactured and subjected to industrial product testing. The first tests indicated that flax based yarns were not sufficiently robust to withstand washing cycle testing. An alternative yarn production process has been applied to flax/ cotton blends to produce a yarn having different characteristics. This has been submitted to manufacturers for incorporation into industrial matting and further testing.

Filtration and pollution remediation product manufacturers
Flax and hemp fibre and technical fabrics have been assessed for suitability as surface active filter media by filter manufacturers. A particular use is as a material for removal of

metals from wastewater. The flax, in particular, has metal sorption characteristics which are thought to be useful in this application. The fabrics have interested potential users both as a support matrix for more active materials and for biofilms. An application for further funding in this area of research is being submitted with industrial support under an EPSRC managed programme (Waste Minimisation, Reuse, Recycling and Recovery - WMR3) in 1998. Activated carbon materials derived from flax and hemp have been assessed as being useful for air pollution remediation applications, funding to support this research for 3 years (£200,000) has been awarded.

In the course of the 'Fibrelin plus' project which preceded this research, possible industrial uses of flax fibre and related materials were identified. These earlier findings are, if anything, reemphasised by the work in this project. There is every reason to suppose that oil pollution remediation, soil erosion control and related uses are a potential market. In addition to this, the viability of flax non-woven fabrics as an agrotextile to create and control a microclimate for seed germination and growth has been established.

3.9 Economic assessment (Silsoe Research Institute)

All crops except for milkweed are potentially profitable in at least one market.
Under the current agricultural support arrangements, the following crops have the greatest potential profitability if the technical problems are solved:

- Wheat, rape and linseed straws are all by-products and are amongst the most profitable in the short-fibre biocomposites markets,
- Flax and hemp are potentially the most profitable crops for the long-fibre textiles and chemical pulping markets.

All of the crops are modelled using existing agricultural support policies. For those crops where support policies do not currently exist, a range of support payments has been evaluated.
If support payments of c. £ 600/ ha (similar to flax and hemp) are made to the 'un-supported' crops then the following become potentially profitable if the technical factors associated with their production and processing can be optimized:

- Hollyhock, marshmallow and nettle for long fibre pulping and textiles markets,
- Reed canary grass, miscanthus and poplar coppice for short fibre biocomposites markets.

The potential profitability of the above crops can be further enhanced if the support environment is guaranteed over the 20-25 years stand lives that these perennial crops can have.

Comments and caveats
To realize this potential profitability may require the optimization of a number of technical factors, such as drying costs, which are highlighted in this subsection. This subsection also includes those issues that are important to the interpretation of the results. Additionally, successful commercialization depends on a number of issues relating to commercial acceptability and the current state of relevant industrial processing technology and investment in the UK (see Annex 2, Annex 5 & Appendix C).

- An established UK fibre cropping industry could potentially require 50-100,000 ha of land.
- The impact of the range of potential technical factors and subsidy for hollyhock and poplar coppice shows that if hollyhock were to be competing against a maximum farm

gate price of £30 /t dm then no scenarios are profitable if either yield level, support payment or production costs are at their worst case. If poplar coppice were to be competing against the same price then no scenarios are profitable if either harvesting, storage and drying costs, support payments or production costs are at their worst case. Increasing the yield potential of poplar coppice from the worst to the best case increases the proportion of profitable scenarios from c. 2% to c. 3%. If any other included item is at its best case then only 2% of scenarios are profitable. The other perennial crops are likely to be similar.

- Establishment costs are an important area of cost for hollyhock, marshmallow, nettle, miscanthus and poplar coppice.
- The lack of suitable approved crop protection chemicals gives rise to high weed control costs for hollyhock, marshmallow and nettle at present.
- The harvesting systems of flax, hemp, hollyhock, marshmallow, nettle, reed canary grass, miscanthus and poplar coppice have the potential to be further improved.
- The effect of quality and variability of dew retting on the functioning and economics of the decortication system for long fibre production have yet to be researched.
- Profitable and practical storage and drying systems for retted straws and winter-harvested crops are not fully researched in the context of the fibre market. These costs are important sensitivities to the potential profitability of these crops. Results and techniques for drying and storage of biomass coppice are relevant but not sufficient.
- The long-fibres of nettle and flax can technically be upgraded to be competitive with wool and cotton, but shive monitoring and control during decortication is a serious current limitation.
- The profitability of short-fibre biocomposites manufacture depends on very small margins. The resolution of this study is only high enough to determine the general areas of potential profitability, so estimation of those margins is not sufficiently good for confident predictions to be made in this market.

4 Remarks on milestones (listed in Annex 7)

Overall remarks by coordinator.
Because of difficulties, anticipated in the CSG7 for the project, in growing some of the crops, quantities available were in some cases very much smaller than was intended despite strenuous efforts by ADAS. As a result little of these materials was available for processing and it was available later in the project. Subsequent work was tailored to the materials available, which had to be husbanded more carefully to provide maximum information. The milestones in CSG13 section 3, completed against the original target dates, reflect these problems. As much of the work programme has been completed on time as was possible to do within the limitation of materials. Plans and priorities have been reviewed at project meetings, and adjusted to meet as closely as possible the overall project objectives by the end of the project.

ADAS
Milestone 01/03 was extended into the final year in order to provide further material for the collaborators to evaluate from crops of reed canary grass, nettle, milkweed, marshmallow and hollyhock. This material was provided. Information on the agronomic inputs and yields of fibre crops was provided for use in achieving milestone 09/01

(economics). That some crops would give low yields or would not grow successfully was anticipated in the CSG7 for the project.

ARINI
All milestones for fibre quality have been met in full. The achievement of the milestone for completing the analyses was behind schedule due to the need to find a replacement for a key member of staff who moved to another job. However all the work was subsequently completed by the end of the project.

BioComposites Centre
Objective 4: Pulp and Paper. With the exception of milkweed, hollyhock and marshmallow, all crop materials were evaluated for the suitability as feed-stocks for mechanical, semi-chemical and chemical pulps. The chemical composition and fibre length characteristics of the crop materials were also evaluated.

Objective 5: Wood-based Panels. With the exception of milkweed, hollyhock and marshmallow, all crop materials were evaluated for their suitability as feed-stocks for medium density fibreboard (MDF) using urea formaldehyde (UF) resin. With the exception of milkweed, all crop materials were evaluated as feed-stocks for particleboard using both UF and isocyanate (MDI) resin.

Silsoe Research Institute
With the exception of milkweed, marshmallow, hollyhock and nettle, milestones were met. Lateness and shortage of these crop materials restricted what fibre extraction was possible and also delayed other partners' work.

University of Leeds
The objectives of the project have been broadly met. During the course of the project there was some unavoidable delay in the provision of fibre samples to Leeds leading to an adjustment of milestones agreed between the project partners. In addition, following input from industrial interests and initial evaluation of commercial potential, there has been a degree of refocussing of priorities. This process has been fully discussed and agreed at the regular six monthly co-ordination meetings of the project partners.

5 Intellectual property

No intellectual property has been developed in the project.

6 Further research

ADAS
1. Establish the longevity of reed canary grass and miscanthus as fibre crops.
2. Investigate weed control techniques for nettles and hollyhocks.
3. Establishing retting requirements and conditions for hemp and flax.
4. Comparison of the effect of harvest date on fibre quality of nettle, miscanthus and reed canary grass.
5. Investigate methods of destruction of reed canary grass and miscanthus at the end of the production period.
6. Survey pest and disease problems of commercial hemp crops.

7. Comparison of varieties of wheat, oilseed rape, linseed, flax and miscanthus for fibre production.
8. Investigate the optimum harvesting time of poplar coppice and age of coppice growth for use in panelmaking.
9. Evaluate the yield potential and reliability of production of fibre crops across a range of sites in the UK over several seasons.
10. Investigate the effect of plant density on yield, suitability for harvesting and fibre quality of flax and hemp.
11. Investigate the effect of different desiccation regimes and weather during desiccation on retting and fibre quality of flax.

(ARINI to be added when LE provides)

Agricultural Research Institute of Northern Ireland

1. No rapid method for estimating shiv content of flax fibre is available at present. As shiv content is the major quality factor limiting the uses for decorticated fibre there is a need for research to develop technologies which have looked promising in initial studies, such as image analysis and near infrared reflectance.
2. It is also clear that degree of retting significantly affects the performance of fibre extraction equipment and the potential uses of fibre. Further research needs to be carried out into evaluating how the correct degree and uniformity of retting can be achieved and measured in crops under management systems appropriate for industrial crops.

BioComposites Centre

1. There would appear to be little benefit to be gained from conducting further pulping studies. This work has demonstrated that the grasses e.g. miscanthus, reed canary grass and wheat straw would be suitable raw materials for chemical pulps. To make this a commercial reality, further research efforts should be directed towards the ongoing development of economically viable small scale chemical pulping. The issue of raw material variability in the chemical pulping of long fibres could also be addressed by the development of rapid on-line assessment techniques designed to give estimates of shiv content and/or chemical composition.
2. Further work on coppice poplar, in particular to address the issue of particle size and geometry on particleboard properties, would clearly be of benefit in confirming whether the material was suitable for meeting all product property requirements. Additional studies aimed at determining the effect of species / variety / clone, age and site on product properties would be justified, in order to determine key agronomy variables and the potential variability of the raw material; inclusion of coppice willow in any study should also be considered. Further work on other crop materials to optimise particle size and geometry could lead to substantial improvements in product properties, and hence improved industrial acceptability.

3. To address the concerns expressed by MDF manufacturers, further work aimed at assessing the longer term effects on the production process of processing crop materials should be carried out. This work should be limited to those materials which appear to be the most competitive in terms of the estimated price of supply. Work on

coppice willow would also be beneficial, since this could address concerns relating to colour changes in the product; willow is stated to retain its white colour after harvesting and during storage unlike poplar, which has a tendency to darken.

Silsoe Research Institute - economics

The overall aim of this project (NF 0303) has been to provide a 'first impression' of the potential of the 12 crops as UK grown fibre crops. The economic evaluation has established a wide platform from which further, more focused, projects could be launched. Three main areas are proposed:

1. Focussing the economic analysis in conjunction with appropriate technical research is required in order that the main technical and industrial impediments to successful commercialization can be identified, quantified and optimally solved,
2. Evaluating a wide range of agricultural policy scenarios, especially during this period of policy reform, will help to provide a context within which to assess the risks of long-term industrial investment into any of these crops,
3. Enlarging this economic analysis to include the environmental life cycle assessment of the important commercial opportunities will help identify whether continuing to develop a UK fibre crop industry will result in a net environmental gain for the UK.

Silsoe Research Institute – harvesting and drying

1. Drying of fibre crop material needs to be investigated to quantify in more depth than done in Annex 4c the costs and rates for various possible systems. Such an investigation would define the costs and benefits, and could quantify the risks of quality loss using UK weather data and simple drying models.

2. If flax is to achieve its potential yield in a combine-based system and retain the subsidy, the performance of the combine in dense crops of flax needs to be improved. Such an improvement may be possible by mowing following seed head stripping using the SRI stripper rotor.

3. Decortication of hemp is challenging the decorticator system. Further development is needed to increase processing rate and reduce wrapping.

4. University of Leeds School of Textile Industries The factors limiting the potential of flax are broadly, the lack of cleanliness and the absence of quality measures to quantify quality. These two areas must be addressed to fully realise the commercial potential of flax and hemp, suggested projects are :

(a) A project to establish a modular processing line, based on existing commercial equipment, to clean up the basic, decorticated raw material and provide a better quality fibre (1 year project).

(b) A two stage project to establish effective and objective quality measures for flax (and hemp) fibre. The first stage to review the mechanisms used for quality control in related industries, particularly automated and on-line sytems based on optical and spectroscopic detection of shiv etc. The second stage to evaluate the applicability of these to flax (and hemp) and develop and validate a viable system of quality measurement (1 year first stage followed by 2-3 year second stage)

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