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Site does not affect the fibre content ranking order among fibre hemp (*Cannabis sativa* L.) varieties

Die Fasergehaltsreihung verschiedener Faserhanfsorten (*Cannabis sativa* L.) ist standortunabhängig

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Summary

In growing fibre hemp for textile applications, selecting the variety is very important, as it affects fibre content, fibre quality as well as stem dry matter yield. It was investigated whether the ranking of varieties with respect to their total and long fibre content was affected by the environment. Experiments in Finland (2004) and The Netherlands (2007) were compared. Samples of the bottom, middle, and top of stems were fractioned into wood, long fibre and tow. Retting losses were determined separately, and fibre percentages were calculated based on the dry weight of stems after retting. This method avoids differences in retting losses to appear as differences in fibre percentage and focuses on the ratio in which varieties produce fibre and wood. When the five selected varieties were ranked from low to high total or long fibre percentage, the order was the same for both sites. Highest fibre percentages were found in the middle stem part. The scutched long fibre/total fibre ratio in this stem part was around 90%, irrespective of variety, or site. It is concluded that the effect of the environment on the fibre content of varieties, if any, is small and for practical reasons can be neglected.

Key words: fibre hemp, fibre content, genotype, retting, textiles

Zusammenfassung

Beim Anbau von Faserhanf für textile Verwertungen ist die Sortenwahl sehr wichtig, weil sie den Fasergehalt, die Faserqualität sowie den Trockenmasseertrag der Stängel bestimmt. Wir haben untersucht, ob die Reihung von Sorten bezüglich ihres Gesamt- und Langfasergehaltes von der Umwelt beeinflusst wird. Versuche in Finnland (2004) und in den Niederlanden (2007) wurden verglichen. Hierzu wurden Proben vom unteren, mittleren und oberen Abschnitt der Stängel fraktioniert in Holz, Langfaser und Werg. Die Röstverluste wurden unabhängig davon bestimmt, und die Fasergehalte wurden berechnet auf Basis der Stängel-Trockenmasse nach Röstung. Auf diese Weise wird vermieden, dass Unterschiede in den Röstverlusten als Fasergehaltsunterschiede erscheinen, und die Sortenunterschiede in Faser- bzw. Holzproduktion werden klar herausgearbeitet. Sortiert man die fünf untersuchten Sorten hinsichtlich der Gesamt- oder Langfasergehalte, so war die Reihenfolge auf beiden Standorten gleich. Die höchsten Fasergehalte fanden sich in der Mitte der Stängel. Das Verhältnis von geschwungener Langfaser zu Gesamtfaser betrug unabhängig von Sorte und Standort ca. 90%. Offenbar ist der Umwelteffekt auf den sortenspezifischen Fasergehalt klein und kann für die Praxis vernachlässigt werden.

Schlüsselworte: Faserhanf, Fasergehalt, Sorte, Röste, Textilien

Introduction

The highest added value in fibre hemp (*Cannabis sativa* L.) production can be obtained by producing high-quality "long fibres" for the finest yarns for fashion textiles, a small but growing market (Van Dam 1999, Cappelletto et al. 2001, Amaducci 2003, Liberalato 2003, Esposito & Rondi 2006). To provide relevant decision support to primary producers it should be known how the amount of fibres of the desired quality could be maximised within a single plant and within a crop.

Farmers producing hemp for textile applications should aim at the optimal combination of stem dry matter yield × fibre content × fibre quality to maximise their profits. The choice of the variety is very important, as it affects all three factors (Bócsa & Karus 1998). Many varieties have been described (De Meijer 1995, Bócsa & Karus 1998, Mediavilla et al. 1999) and fibre hemp is grown in many different environments over a wide range of latitudes. Selecting the most suitable variety for any environment, however, seems complex, because of the possible genotype × environment interactions.

The interaction between genotype (variety) and latitude is important with respect to stem dry matter yield. Some varieties are suitable at certain latitude while others are not. With respect to the effect of the environment on the total and long fibre content of varieties, the picture is less clear. The main objective of the experiments described in this paper is to investigate whether the ranking of varieties with respect to their total and long fibre content is affected by environment. Two contrasting sites at different latitudes, one in Finland, the other in the Netherlands, are compared.

Stem dry matter yield

To maximise stem dry matter production, hemp should be sown as soon as the risk of frost damage is acceptably low, and varieties with a long vegetative growing period should be selected to make optimal use of the length of the growing season (Dempsey 1975, Van der Werf et al. 1994a, Meijer et al. 1995, Ranalli 1999, Lisson & Mendham 2000). The length of the vegetative growing period, however, depends on the interaction between genotype and environment. Hemp is a short-day plant (Tournois 1912, Borthwick & Scully 1954, Heslop-Harrison & Heslop-Harrison 1969), varieties show a wide range of critical day lengths (Amaducci et al. 2008a), and day length obviously differs for different latitudes. To optimise stem dry matter production it is important not to choose a variety that flowers too early at the chosen site, because around flowering, the allocation of dry matter to the stem decreases (De Meijer & Keizer 1994, Van der Werf et al. 1994a, Ranalli 1999, Westerhuis et al. 2009b). The effect of genotype on stem dry matter yield will not be discussed in this paper. Stem dry matter yields for different varieties were published for many different sites. A comparison, e.g., between sites in Italy, the Netherlands, and the United Kingdom was published by Struik et al. (2000).

Fibre content

Although some varieties consistently show relatively high fibre percentages, e.g. Beniko and Bialobrzeskie (Mediavilla et al. 1999, Sankari 2000, Bennett et al. 2006), other varieties are known for their consistently low fibre content, e.g. Tiborszállási (Amaducci 2006, Tofani 2006), the absolute values for a given variety vary widely within and between experiments. Vetter et al. (2002) for instance found in an extensive variety trial in Germany (12 varieties, 4 years, 5 sites) wide ranges in fibre percentages, e.g. for Fedora (12.7-22.6%) and Futura (15.4-22.6%). Presumably, these wide ranges are largely due to differences in retting losses (see below).

Retting losses

Hemp retting, which is comparable to flax (*Linum usitatissimum* L.) retting, is the process in which the fibres are liberated from the surrounding tissues. Moulds (dew retting) or bacteria (water retting) degrade pectins, and in addition, other substances, including proteins, sugars, starch, fats, waxes, tannins and minerals, are removed from the biomass. Cellulose is not readily decomposed, hence merely the woody part of the stems and the cellulose-filled fibre bundles survive retting (Hann 2005).

Fibre percentages are usually calculated by dividing the dry weight of the extracted fibres by the dry weight of the stems before retting (cf. Sankari 2000, Vetter et al. 2002). Consequently, differences in retting losses cause differences in fibre percentages. The thus calculated fibre percentage might be suitable to determine the fibre yield, but it is an inadequate variable to understand underlying botanical processes. Westerhuis et al. (2009a, b) therefore proposed to distinguish between the retting loss percentage (1a) and the fibre percentage after retting (1b)

(1a) Retting loss percentage =
$$100 \times (1 - \text{dry weight retted stems} / \text{dry weight stems})$$
(1b) Fibre percentage =
$$100 \times \text{dry weight fibres} / \text{dry weight retted stems}$$

This fibre percentage (1b), shows in fact the ratio in which fibres and wood are produced and therefore is an important botanical characteristic for fibre hemp. It is different for varieties, but for a given variety independent of sowing density, sowing date, and harvest time (Westerhuis et al. 2009a, b). In contrast with this, Westerhuis et al. (2009b) reported large variability in retting loss percentages and showed that retting loss percentages gradually decreased with increasing stem weight, irrespective of the cause of the higher stem weight, e.g. lower plant density, later harvest, or different stem part.

To compare the samples from both sites properly, a controlled warm water retting procedure was used to avoid the extreme weather dependency that comes along with field retting (Dempsey 1975, Van Dam 1999, Hann 2005, Salmon-Minotte & Franck 2005, Sponner et al. 2005). Over-retting or under-retting and other possible sources of unintended and undesirable differences in fibre content are excluded in this way and retting losses can be determined under controlled conditions.

Because fibre percentages are calculated based on the dry weight after retting the results of the experiments will be difficult to compare with those obtained by other authors who studied the same varieties (e.g. Cromack 1998, Mediavilla et al. 1999, Sankari 2000, Vetter et al. 2002, Amaducci 2006, Bennett et al. 2006).

Stem part

The total fibre content shows a bow-shaped pattern along the stem, with highest fibre percentages in the middle and lower fibre percentages towards both bottom and top (Bredemann 1940, Van der Werf et al. 1994b, Westerhuis et al. 2009a, b). For this reason different stem parts should be taken explicitly into account.

Fibre quality

One particularly important aspect of fibre quality must also be taken into account. To introduce hemp into the fashion textile sector, fibres should be produced allowing the spinning of yarns between Nm 20 and Nm 40. The finer the yarn that can be spun, the higher the value of the raw material is (Ranalli & Venturi 2004, Van Dam & van den Oever 2006). Yarn spinners have high demands with respect to the underlying fibre characteristics fineness, refinability, strength, and homogeneity (Sultana 1992, Van Dam 1999, Allam 2004, Hann 2005, Sponner et al. 2005).

However, these characteristics are only important with respect to the fibres that have passed all processing steps before spinning. The first threshold in processing is scutching and only the long fibres surviving this step ('scutched long fibres') are valuable. Their share in the total fibre fraction can be considered a quality parameter of the raw material (Hoffmann 1957, Allam 2004). 'Scutching tow', the fibre material beaten out of the bundles, can be used for other applications, but not for long fibre spinning.

The total fibre (i.e. 'scutched long fibres' + 'scutching tow') percentage, the scutched long fibre percentage, and the ratio between them will be determined to investigate whether genotype × environment interactions for these variables are present.

Material and Methods

Experimental design

Field experiments were carried out at contrasting sites in Jokioinen (60° 49' N, 23° 28' E), Finland and in Achterberg (51° 58' N, 5° 35' E), The Netherlands. In Jokioinen, twelve fibre hemp varieties were sown on 17 May 2004: Beniko*, Bialobrzeskie*, Chamaeleon, Dioica, Epsylon, Fedora*, Felina, Ferimon, Fibranova, Futura*, Lovrin, and Tiborszállási*. Yield data of this experiment were reported by PAHKALA et al. (2008). On 27 April 2007, five of these varieties (those marked with an asterisk), covering the wide range in fibre content that was found in the Finnish experiment, were sown in Achterberg.

The experimental set-up at both sites was a randomized four-replicate split-plot design with varieties as main plots and harvest dates as sub-plots. The field was ploughed the previous autumn, and prior to sowing the field was harrowed. Seeds were sown with a precision drill at a depth of approximately 3–4 cm at target plant populations of 240 plants m^{-2}, a density within the range appropriate for textile hemp (AMADUCCI et al. 2002a). Distance between rows was 12.5 cm. Harvest plots were 3 m^2 surrounded by at least 1 m border rows to avoid edge effects. No biocides were used. At harvests, dead plants and shed leaves were not collected.

In Finland, the experiment was carried out on a silty clay soil with 4.7% organic matter and pH (H_2O) 6.3. Nitrogen fertilizer was applied at a rate of 120 kg N ha^{-1}. This amount was based on an experiment in 2003 at the same site (PAHKALA et al. 2008). No irrigation was applied. A single harvest was carried out at the beginning of flowering (MEDIAVILLA et al. 1998), as the harvest planned at the end of flowering was compromised by a severe frost on 11 October 2004. At harvests, stems were cut close to soil level (stubble < 5 cm), using a Honda garden tiller with a saw tool (F410/560 S). One replication each of cultivars Beniko and Fedora was discarded, because of damage caused by stormy weather. Per harvested plot, 50 plants were randomly taken and measured for plant height and stem diameter at 10 cm above cut height.

In the Netherlands, the experiment was carried out on a sandy soil with 4.1% organic matter and pH (H_2O) 5.6. Nitrogen fertilizer was applied manually per plot at a rate of 50 kg N ha^{-1}, directly after sowing. This amount was based on a successful hemp experiment at the same site in 2005 (WESTERHUIS et al. 2009a). Because of the dry conditions in April 2007, the field was irrigated one and two days after sowing, on both occasions with approximately 15 mm of water, to ensure uniform germination and emergence. Three harvests were planned with two weeks between subsequent harvests. The middle harvest was planned at the time when 50% of the plants ≥ 100 cm were flowering, meaning that at least one flower, either male or female, was open. This moment was predicted based upon flowering data from earlier experiments. At harvests, stems were manually cut at soil level with pruning shears (no stubble). Per harvested plot, 100 plants were randomly taken, flowering status was recorded and plant height and stem diameter at 10 cm above cut height were measured.

At both sites the dry weights of both stems and remainder, i.e. leaves and inflorescences, were determined on 20 plants following drying for 24 h at 105°C in a stove. The other plants were dried on a drying floor in order to prevent them from decaying during storage and shipment.

Stem selection and sample preparation

Stem selection and sample preparation were different for the sites. From the Finnish trial, for some of the plots a limited number of plants were available. The minimum length for processing on the Flemish mill was 50 cm and all stem parts in a sample should have equal length. To study bottom, middle and top of the same plants, only plants with a height ≥ 150 cm could be used. The smaller plants were discarded. A variable number of stems (minimal 15) were processed, depending on the availability of undamaged stems, their height, and the diameter of the PVC tubes that were used for retting. The stems were defoliated and from each individual stem the bottom 50 cm, the exact middle 50 cm and the top 50 cm stem part were cut (Fig. 1 top). Samples were tied up with tie-ribs and remainders were discarded.

From the Dutch trial, a large share of the plants was shorter than 150 cm hence too short to cut into three 50 cm parts. Therefore, it was decided to cut bottom and

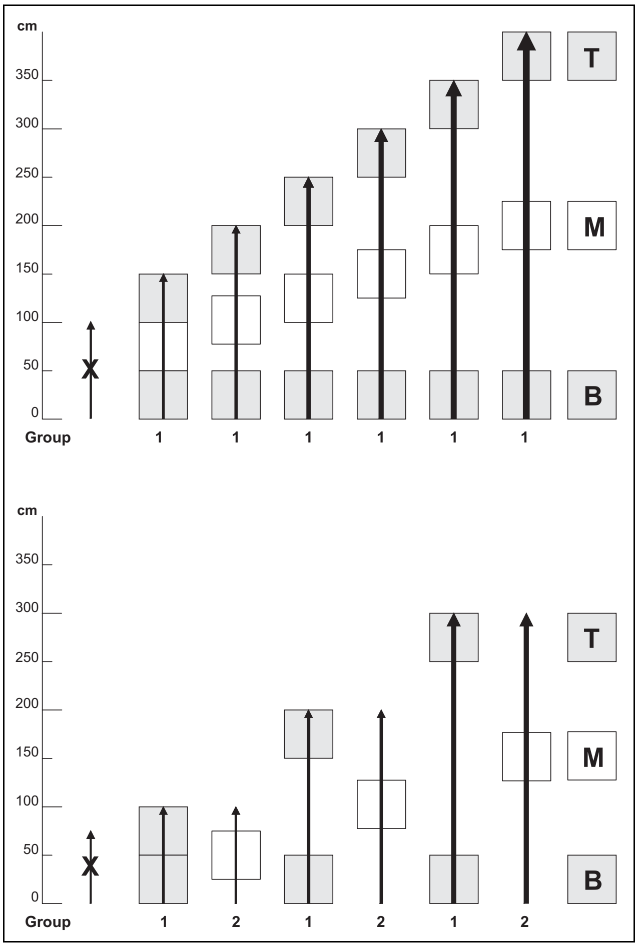

Fig. 1: Stem partitioning before processing. In Finland (top) plants shorter than 150 cm were discarded (X). A variable number of plants (minimal 15) were processed, depending on availability and size. Stem parts originated from the bottom (B), middle (M), and top (T) 50 cm of the same stems. In The Netherlands (bottom) plants shorter than 100 cm were discarded (X). Two comparable groups (1, 2) of 50 stems were assembled. Stem parts originated from the bottom (B), middle (M), and top (T) 50 cm of the stems. B and T stem parts were cut from the same stems (group 1); M stem parts were cut from group 2.
Fraktionierung der Stängel vor der Aufbereitung. In Finnland (oben) wurden Pflanzen unter 150 cm verworfen (X). Eine variable Zahl von Pflanzen (mindestens 15) wurde in Abhängigkeit von Verfügbarkeit und Größe aufbereitet. Die Stängelfraktionen stammten von den unteren (B), mittleren (M) und oberen (T) 50 cm derselben Stängel. In den Niederlanden (unten) wurden Pflanzen unter 100 cm verworfen (X). Zwei ähnliche Gruppen (1, 2) von je 50 Stängeln wurden zusammengestellt. Die Stängelfraktionen stammten von den unteren (B), mittleren (M) und oberen (T) 50 cm der Stängel. Die B- und T-Stängelabschnitte wurden von derselben Stängelgruppe (Group 1) genommen, die M-Stängelabschnitte von der anderen Gruppe (Group 2).

top part from the same plants, but the middle section from a parallel group of plants. Consequently, plants < 100 cm were discarded and plants ≥ 100 cm were processed. Per harvested plot, 100 stems were randomly taken and were defoliated. Two comparable groups of 50 stems were assembled. From the first group the bottom 50 cm and top 50 cm stem part were cut, from the second group the exact middle 50 cm stem part was used (Fig. 1, bottom). Samples were tied up with tie-ribs and remainders were discarded.

Fibre extraction

Industrial processing of fibre hemp into high quality yarns in principle is similar to linen production from flax (Sponner et al. 2005). Hann (2005) and Salmon-Minotte & Franck (2005) described this linen production chain accurately and in detail. Because of the small sample size as compared to industrial processing, a traditional fibre extraction method was used. With respect to the procedural steps and the final products, the methods, however, are identical.

The method consisted of four steps: retting, breaking, scutching and cleaning. Before retting, before breaking, and after cleaning, weighing took place to determine the initial dry weight, the retting losses, and the amounts of scutched long fibre and scutching tow. The weight of the wood was estimated by subtracting retting losses and total fibre weight (i.e. scutched long fibre + scutching tow) from the stem weight after retting. To compare the different batches properly, weighing was always preceded by conditioning the materials at 19°C and 73% humidity for at least 48 h (Van den Oever et al. 2003) and the machinery was not adjusted during the experiment.

Retting

Warm-water retting took place in 120 cm high PVC tubes with a 16 cm diameter and closed bottom. Prior to retting the cylinders were filled with tepid tap water. This water, used to wash away contaminants, was drained after 2 h. The cylinders were placed in a retting basin and filled with tap water of 34°C. Stems were completely submerged, but water exchange between cylinders was avoided. Retting was performed at 34°C in 96 h after which the bundles were carefully washed with tepid water. Excess water was drained away by placing the bundles vertically on a grating above a drain. Next, the bundles were dried on a drying floor for 4 d at 27°C.

Breaking

To separate fibres and wood the tie-ribs were removed and the stems were arranged in an even layer, and then fed into a flax breaker consisting of a double series of ribbed breaking rollers. These heavyweight rollers put pressure on the stems by means of a spring system. As a result, stems were flattened and the brittle wood was broken into shives, most of which fell through the machine, while the flexible fibres passed under the rollers easily.

Scutching

Scutching was performed on a Flemish mill with rotary blades that beat the broken stems in such a way that remaining shives and tow were separated from the long fibres. Both sides of the samples, the upper and lower part of the stem part, were manually fed through the rotary blades eight times; after four times the bundle was turned inside out.

Because the end of the sample had to be held in the hand while scutching the other side of the sample, all stem parts in a sample had to be of uniform length. If shorter stem parts were accepted, all the fibre material in these shorter parts, both scutched long fibre and scutching tow, would end up in the tow section. The aim, however, was to distinguish between these fractions.

Cleaning

After scutching, the long fibres and tow were cleaned by hand to remove any remaining shives and tow. After fibre extraction, conditioning, and weighing, the amounts of scutched long fibre and scutching tow were determined and the weight of the wood was estimated. Top 50 cm tow was not cleaned, because in this part tow could not easily be separated from the wood. Consequently, total fibre weight and hence total fibre percentage could not be calculated for this stem part.

Statistical analysis

Statistical analyses of the data ($p<0.05$) were conducted using GENSTAT® release 11.1. following tests for normality:

Multiple linear regression analyses were performed to analyse the ratios between the stem weight before and after retting and between the total fibre and wood fractions for the hemp produced in The Netherlands. Stepwise addition or subtraction of terms was carried out to define the most suitable model to use in general linear modelling, i.e. the model with the minimum residual mean squares. There were no statistical or biological reasons to test non-linear models.

Analyses of variance (ANOVAs) were calculated for all other variables. Means, standard errors of differences of means (SEDs), and degrees of freedom are reported.

Results

First it is explained which method was used to compare the two sites. Next, the results of the Finnish trial with twelve varieties are reported to show the large differences in long and total fibre content between the varieties and the similarity between them with respect to the patterns along the stem. This is followed by a comparison between the sites for the five varieties that were grown at both sites. Finally, retting losses are presented. Characteristics of the harvested and processed hemp are presented in Tab. 1.

How to compare the sites: a problem and a solution

In Westerhuis et al. (2009a, b), the ratios between the total fibre weight per stem part and the weight of the wood per stem part were analysed with multiple linear regression analyses. Based on these papers different total fibre/wood ratios were expected for different varieties and stem parts. The aim was to investigate and quantify the differences between sites using the same statistical method. In Fig. 2a (middle stem part) and 2b (bottom stem part) therefore, the total fibre weight per stem part was plotted against the wood weight per stem part for the five varieties. The figures clearly show the large differences between varieties and the absence of an important variety × stem part interaction. A linear regression analysis (Tab. 2a) revealed that the weight of the wood (53.9%), the variety (+ 42.7%) and the stem part (+1.6%) together accounted for 98.3% of the variance in total fibre weight.

Tab. 1: Varieties, harvest dates, temperature (T) sum at harvest, plant height, stem diameter, volume share of processed plants, density at full emergence, density at harvest and flowering percentage in two experiments on fibre hemp in Jokioinen (Finland) in 2004 and Achterberg (The Netherlands) in 2007. The volume share of the processed plants is calculated according to Amaducci et al. (2002a). Flowering data were only recorded in the Netherlands.
Sorten, Erntetermine, Temperatur(T)-Summen bis zur Ernte, Pflanzenhöhe, Stängeldurchmesser, Anteil verarbeitbarer Pflanzen, Pflanzendichten nach Feldaufgang sowie zur Ernte und Blühanteil in zwei Experimenten mit Faserhanf in Jokioinen (FIN, 2004) und Achterberg (NL, 2007). Der Anteil verarbeitbarer Pflanzen wurde berechnet nach Amaducci et al. (2002a).

Variety	Harvest	date	T-sum (base = 0°C)	Plant height (cm)	Stem diameter (mm)	Volume share (%)	Density at emergence (m^{-2})	Density at harvest (m^{-2})	Flowering (%)
Jokioinen, Finland									
Fedora	H1	31-8	1455	209	8.1	92	182	107	
Ferimon	H1	2-9	1482	214	7.9	91	157	105	
Bialobrzeskie	H1	3-9	1500	222	8.2	95	217	108	
Felina	H1	7-9	1555	219	8.0	92	179	133	
Epsylon	H1	9-9	1570	226	8.8	94	164	107	
Beniko	H1	10-9	1583	213	8.3	94	206	100	
Futura	H1	14-9	1638	236	9.5	95	160	84	
Tiborszállási	H1	15-9	1651	250	9.7	96	198	91	
Chamaeleon	H1	16-9	1659	239	10.4	97	135	83	
Lovrin	H1	20-9	1704	243	9.9	96	144	112	
Dioica	H1	23-9	1733	260	11.5	98	133	71	
Fibranova	H1	29-9	1793	247	10.6	98	88	62	
Achterberg, The Netherlands									
Beniko	H1	9-7	1207	154	6.2	98	130	130	2
	H2	23-7	1465	173	6.3	99		121	27
	H3	6-8	1709	176	6.2	98		126	84
Bialobrzeskie	H1	9-7	1207	162	5.6	98	136	148	24
	H2	23-7	1465	190	6.2	98		129	51
	H3	6-8	1709	188	5.9	99		124	94
Fedora	H1	9-7	1207	142	4.6	96	250	235	6
	H2	23-7	1465	163	4.9	98		242	42
	H3	6-8	1709	157	4.8	97		250	93
Futura	H1	30-7	1582	162	5.0	98	244	228	4
	H2	13-8	1830	176	5.2	98		250	56
	H3	27-8	2067	180	5.4	98		240	97
Tiborszállási	H1	30-7	1582	213	7.8	99	91	89	16
	H2	13-8	1830	232	8.1	99		87	82
	H3	27-8	2067	232	7.7	99		77	97

However, the aim was to investigate whether or not the ratio in which fibres and wood were produced was affected by site. Although Fig. 2a and 2b indicate that the differences between sites are very small, as compared to the differences between varieties, they also show that multiple linear regression analysis is not suitable to analyse the differences between sites. The stems in the Finnish experiment on average were taller and thicker than the stems in the Dutch experiment (Tab. 1), hence their weight was higher. Consequently, the majority of the data points from the Finnish experiment (encircled) are found on the right side of Fig. 2a and 2b, which means that the distribution is unbalanced with respect to site. Moreover, the small number of data points from the Finnish experiment, only one harvest was carried out, did not warrant the calculation of regression lines per site.

This problem was tackled as follows. Westerhuis et al. (2009a) showed that with increasing stem weight the total fibre percentage decreased. The reason is that the linear regression line (2) had a positive intercept (b), which means that with increasing stem weight the positive effect of intercept b on the fibre percentage levels off towards a fibre percentage equivalent to $a/(1+a) \times 100\%$ (Fig. 3).

(2) total fibre weight = $a \times$ wood weight + b

In the Dutch experiment, the stem weight was highest at the last harvest date (H3). Unless a harvest time effect would be present, an extra effect of harvest time besides its effect on stem weight, it would be reasonable to compare the H3 samples by means of an analysis of variance (ANOVA) with the Finnish samples to investigate whether there is a site effect. Because three harvests were carried out in the Netherlands, the number of samples per variety was sufficiently high to warrant a multiple linear regression analysis to check whether the ratio in which fibres and wood were produced depended on harvest time or not. Tab. 2a shows that there were no harvest time terms in the final regression model. This means that for all five varieties and all three stem parts the ratio in which fibres and wood

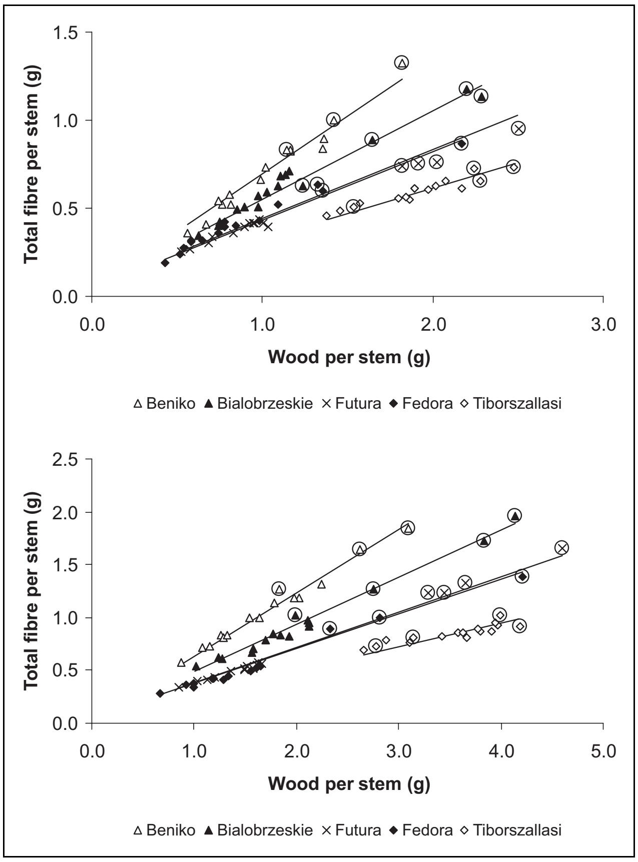

Fig. 2: The total weight of the fibre per stem part plotted against the weight of the wood per stem part. Data obtained from fibre hemp experiments in Achterberg (NL) in 2007 (5 varieties × 3 harvests × 4 replicates), and in Jokioinen (FIN) in 2004 (5 varieties × 4 replicates). The data obtained in the Finnish experiment are encircled. A - The middle 50 cm of stems, B - The bottom 50 cm of stems.

Gesamtgewicht der Fasern pro Stängelabschnitt in Abhängigkeit vom Holzgewicht pro Stängelabschnitt. Daten des Faserhanf-Experiments in Achterberg (NL, 2007, 5 Sorten × 3 Erntetermine × 4 Wiederholungen) und in Jokioinen (FIN, 2004, 5 Sorten × 4 Wiederholungen). Die Daten aus Finnland sind eingekreist. A - mittlere 50 cm , B - untere 50 cm der Stängel.

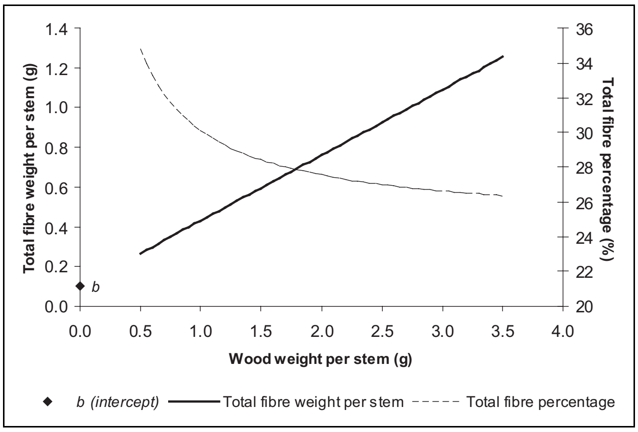

Fig. 3: Total fibre weight per stem (g) and total fibre percentage (%) against the wood weight per stem (g) for a linear regression line $y = ax + b$, with $a = 0.33$ and $b = 0.1$. With increasing stem weight, the fibre percentage decreases, although the ratio in which fibres and wood are produced does not change.

Gesamtgewicht der Fasern pro Stängel (g) und Fasergehalt (%) in Abhängigkeit vom Holzgewicht pro Stängel (g) als lineare Regression y = ax + b, mit a = 0,33 und b = 0,1. Mit zunehmendem Stängelgewicht nimmt der Fasergehalt ab, während sich das Verhältnis von produzierter Faser:Holz nicht ändert.

were produced was not significantly different for different harvest times, confirming the results of WESTERHUIS et al. (2009a, b). Therefore, it was decided to compare the samples obtained at H3 in the Netherlands with the samples of the Finnish experiment by means of ANOVA.

Comparisons between the twelve varieties in Finland

There were large differences in total fibre and scutched long fibre percentage between the twelve varieties (Tab. 3). Differences were also present in the ratio between them. For these three characteristics, a variety × stem part interaction was found.

The twelve varieties showed large differences in total fibre percentage. The ranges in bottom (20–39%) and middle (24–42%) stem parts were in the same order of magnitude. In both stem parts, Beniko showed the highest total fibre percentage and Tiborszállási the lowest. For Chameleon, Dioica, Fibranova, and Futura the total fibre percentage was not significantly different in the bottom and middle stem part, whereas the other eight varieties showed highest total fibre percentages in the middle stem part.

The twelve varieties also showed large differences in scutched long fibre percentage for bottom (13–32%), middle (22–37%) and top (16–24%) stem parts. In all three stem parts, Beniko showed the highest long fibre percentage. Tiborszállási showed the lowest long fibre percentage, but the differences with Lovrin (middle and top stem part), and Futura and Epsylon (top stem part) were not significant. For all varieties, except Dioica, the highest scutched long fibre percentage was found in the middle stem part. In Dioica, no significant difference was found between the bottom and middle stem part.

In the bottom stem part, the scutched long fibre/total fibre ratio was different for varieties (range 64–81%). It was highest in, among others, the four varieties with the highest total fibre percentages (Beniko, Bialobrzeskie, Dioica, Chamaeleon) while it was lowest in, among others, Tiborszállási, the variety with the lowest total fibre percentage. In the middle stem part, the scutched long fibre/total fibre ratio was not different for varieties (range 84–91%). It was higher in the middle stem part than in the bottom stem part. For Chamaeleon, Dioica, and Beniko, however, this difference was not significant.

Comparisons between the two sites

For the five varieties that were selected for sowing at both sites the samples obtained at the third harvest time in the Netherlands were compared by means of ANOVAs with the samples obtained at the single harvest time in Finland (Tab. 4).

There was no main site effect, but the site × variety × stem part interaction was significant ($p<0.05$). The effects of site and stem part on the total fibre percentage, however, were small as compared to the effect of variety. When the five varieties per stem part were ranked from low to high total fibre percentage, the ranking was the same for both sites. Lowest total fibre percentages were found in Tiborszállási and highest in Beniko. The differences between Futura and Fedora were small and not significant in the bottom stem part.

Tab. 2: Maximum multiple linear regression models for a fibre hemp experiment in The Netherlands in 2007 (5 varieties × 3 harvest times × 3 stem parts). a. regression of total fibre weight on wood weight, b. regression of the stem weight after retting on the stem weight before retting. All non-significant terms are included in the residual term. d.f. = degrees of freedom, s.s. = sum of squares, m.s. = mean sum of squares, F pr. = F probability.
Multiple lineare Regressionsmodelle für das Faserhanf-Experiment in den Niederlanden (2007, 5 Sorten x 3 Erntetermine x 3 Stängelabschnitte). a – Regression vom Gesamt-Fasergewicht auf das Holzgewicht, b – Regression vom Stängelgewicht nach der Röste auf das Stängelgewicht vor der Röste. Alle nicht-signifikanten Effekte sind im Restfehler enthalten. d.f. = Freiheitsgrade, s.s. = Summe der Abweichungsquadrate, m.s. =Mittlere Abweichungsquadrate, F pr. = Irrtumswahrscheinlichkeit.

Fitted terms (p < 0.05)	d.f.	s.s.	m.s.	v.r.	F pr.	Variance accounted for (%)
a. Total fibre/ Wood						
1. Wood	1	8.7936895	8.7936895	17072.71	<.001	62.7
2. Wood × Variety	4	4.5530141	1.1382535	2209.89	<.001	95.3
3. Wood × Stem part	2	0.4379532	0.2189766	425.14	<.001	98.5
4. Wood × Variety × Stem part	8	0.0736033	0.0092004	17.86	<.001	99.0
5. Variety	2	0.0295166	0.0147583	28.65	<.001	99.3
6. Stem part	4	0.0068601	0.0017150	3.33	0.012	99.3
7. Variety × Stem part	8	0.0088330	0.0011041	2.14	0.035	99.3
Residual	150	0.0772609	0.0005151			
Total	179	13.9807309	0.0781046			
b. Retted/unretted stem weight						
1. Stem weight before retting	1	205.928989	205.928989	657862.44	<.001	99.8
2. Variety	4	0.259733	0.064933	207.44	<.001	99.9
3. Stem weight before retting × Harvest	2	0.038657	0.019329	61.75	<.001	99.9
4. Stem weight before retting × Stem part	2	0.075750	0.037875	121.00	<.001	99.9
5. Stem weight before retting × Variety	4	0.027193	0.006798	21.72	<.001	100.0
6. Stem weight before retting × Stem part × Harvest	4	0.025634	0.006408	20.47	<.001	100.0
Residual	162	0.050710	0.000313			
Total	179	206.406666	1.153110			

The total fibre percentages were higher in the middle stem parts than in the bottom stem parts for all varieties at both sites. For Futura in Finland the difference, however, was not significant. In Finland, the difference between the bottom and middle stem part was small as compared to the Netherlands.

In the bottom stem part, Tiborszállási, Fedora, Futura, and Bialobrzeskie showed similar total fibre percentages at both sites, whereas Beniko showed slightly higher total fibre percentages at the Finnish site. In the middle stem part, Tiborszállási and Beniko showed similar total fibre percentages at both sites, whereas Fedora, Futura, and Bialobrzeskie showed higher total fibre percentages at the Dutch site.

As for the total fibre percentage, the effects of site and stem part on the scutched long fibre percentage were small in comparison with the effect of variety.

For all stem parts, the scutched long fibre percentage was higher at the Dutch site than at the Finnish site and the difference between the sites increased from the bottom stem part to the top stem part. At both sites and for all varieties, the scutched long fibre percentage was highest in the middle stem part.

For all varieties, the scutched long fibre percentages were higher at the Dutch site than at the Finnish site. For Tiborszállási, however, the difference was not significant. When the five varieties are ranked from low to high scutched long fibre percentage, at both sites the order was the same as for the total fibre percentage: lowest long fibre percentages were found in Tiborszállási and highest in Beniko. At both sites, the differences between Futura and Fedora were not significant.

In the middle stem part, no differences between sites or varieties were present with respect to the scutched long fibre/total fibre ratio. In all cases, it was around 90%. In the bottom stem parts, the scutched long fibre/total fibre ratio was lower at the Finnish site (74%) than at the Dutch site (84%), and Tiborszállási (72%) and Fedora (73%) showed a significantly lower ratio than Futura (82%), Beniko (83%), and Bialobrzeskie (85%).

Retting losses

Retting losses were analysed with multiple linear regression (Tab. 2b) as in Westerhuis et al. (2009b). The analysis was only performed for the Dutch experiment for reasons mentioned above.

There was a linear relationship between the stem weights before and after retting. Fig. 4 shows that with increasing stem weight the absolute retting losses increased. The retting loss percentage, however, decreased with increasing stem weight and levelled of towards about 15%.

The analysis (Tab. 2b) showed that stem weight before retting accounted for 99.8% of the variance in stem weight after retting. A small but significant difference between varieties was present (+ 0.1% explained variance). Variability was largest in the top part of the stems.

Tab. 3: Total fibre percentage, scutched long fibre percentage and scutched long fibre / total fibre ratio for 12 fibre hemp varieties, in a variety trial in 2004 in Jokioinen, Finland. B = Bottom stem part, M = Middle stem part, T = Top stem part; Avg = average, s.e.d. = standard error of differences, d.f. = degrees of freedom, F pr. = F probability. Varieties are ranked in order of total fibre percentage of the bottom stem part. Underlined varieties were also used in the experiment in Achterberg, The Netherlands.
Gesamt-Fasergehalte, Gehalte an geschwungener Langfaser und Verhältnisse geschwungene Langfaser : Gesamtfaser für 12 Faserhanfsorten in einem Sortenversuch 2004 in Jokioinen (FIN). B = unterer, M = mittlerer, T = oberer Stängelabschnitt; Avg =Mittelwert, s.e.d. = Standardfehler der Differenz, d.f. = Freiheitsgrade, F pr. = Irrtumswahrscheinlichkeit. Die Sorten sind sortiert nach Gesamt-Fasergehalt im unteren Stängelabschnitt. Unterstrichene Sorten wurden auch in dem Versuch in Achterberg (NL) geprüft.

Variety	Total fibre (%)			Scutched long fibre (%)				Ratio (%)		
	Stem part			Stem part				Stem part		
	B	M	Avg	B	M	T	Avg	B	M	Avg
Tiborszállási	*19.9*	*23.6*	21.7	*13.1*	*21.5*	*15.6*	16.7	*66*	*91*	78
Lovrin	*23.6*	*26.7*	25.1	*17.1*	*23.9*	*17.4*	19.5	*73*	*89*	81
Fedora	*26.0*	*30.3*	28.2	*18.0*	*26.9*	*18.3*	21.0	*68*	*88*	78
Futura	*26.7*	*28.0*	27.3	*19.8*	*24.1*	*16.6*	20.1	*74*	*86*	80
Epsylon	*27.1*	*29.9*	28.5	*17.4*	*25.2*	*17.7*	20.1	*64*	*84*	74
Felina	*27.5*	*31.3*	29.4	*17.8*	*26.4*	*19.7*	21.3	*64*	*84*	74
Ferimon	*28.3*	*31.6*	30.0	*19.4*	*27.1*	*18.5*	21.7	*68*	*85*	77
Fibranova	*30.0*	*30.2*	30.1	*22.6*	*25.8*	*18.7*	22.4	*75*	*86*	80
Chamaeleon	*31.4*	*32.0*	31.7	*25.1*	*27.9*	*18.9*	24.0	*80*	*87*	83
Dioica	*31.7*	*31.3*	31.5	*25.4*	*27.1*	*19.8*	24.1	*80*	*87*	83
Bialobrzeskie	*32.1*	*34.2*	33.2	*25.8*	*30.1*	*21.4*	25.8	*80*	*88*	84
Beniko	*38.8*	*41.7*	40.3	*31.7*	*37.0*	*24.1*	30.9	*81*	*88*	84
Avg	28.6	30.9	29.8	21.1	26.9	18.9	22.9	73	87	80
s.e.d.		*0.78*			*1.33*				*3.5*	
d.f.		*65*			*99*				*65*	
F pr. Variety × Stem part		*< 0.001*			*< 0.001*				*< 0.001*	

Discussion

Raw materials

The Finnish hemp on average was taller and thicker than the hemp produced in the Netherlands. This was probably mainly due to differences in crop density at emergence and to severe thinning (on average 40%) of the crop between full emergence and harvest in Finland, whereas in the Netherlands almost no thinning (on average 4%) occurred. Hemp stems are thinner and shorter with increasing plant density (Van der Schaaf 1963, Jakobey 1965, Höppner & Menge-Hartmann 1994, Van der Werf et al. 1995, Amaducci et al. 2002b, 2008b, Westerhuis et al. 2009a). The severe thinning in Finland was possibly caused by the higher amount of nitrogen that was applied, because thinning in hemp increases with increasing N-fertilisation (Höppner & Menge-Hartmann 1994, Van der Werf & van den Berg 1995, Amaducci et al. 2002a, Vetter et al. 2002).

The processed plants were considered representative for the harvested plots. Although the number of discarded plants was considerable, their contribution to the harvested volume (Amaducci et al. 2002a) was small. From the Finnish plots on average 5% (range 2-9%) of the harvested volume could not be used for processing, from the Dutch plots on average 2% (range 1-4%).

Total fibre percentage

The experiment in Finland showed that varieties were very different with respect to their total fibre content (Tab. 3). Based on that experiment five varieties were selected, covering the wide range in fibre content found, for a comparative study on a contrasting site in the Netherlands.

The main objective was to investigate whether the ranking of varieties with respect to their total fibre content was affected by site. A main site effect, however, was absent, showing that neither of the sites on average showed significantly higher fibre percentages. Although total fibre percentage depended on a site × stem part × variety interaction (Tab. 2), the effect of variety was very dominant and not compromised by the interaction (cf. Fig. 2a and b). Consequently, the ranking of the varieties with respect to their total fibre percentage based on the dry weight of the stems after retting was not affected by site.

Disentangling the three-way interaction site × stem part × variety, differences were encountered, which were possibly due to differences in harvest technique and plant size between the sites, rather than to differences in the ratio in which any variety produced fibres and wood.

Harvest technique

Based on the findings of Bredemann (1940), van der Werf et al. (1994b) and Westerhuis et al. (2009a, b) higher total fibre percentages were expected in the middle stem part than in the bottom stem part. For all varieties grown at the Dutch site this difference was present (4-8 percent point).

In Finland, however, the differences were smaller (1-4 percent point) and not significant for Futura. Also in Chamaeleon, Dioica, and Fibranova, varieties that were only grown in Finland, no significant difference between bottom and middle stem part was found (Tab. 3).

Probably this difference between sites was caused by the different harvest techniques. Whereas in the Netherlands

Tab. 4: Total fibre percentage, scutched long fibre percentage and scutched long fibre / total fibre ratio for 5 fibre hemp varieties in two variety trials in 2004 in Jokioinen, Finland and in 2007 in Achterberg, The Netherlands. B = bottom stem part, M = Middle stem part, T = Top stem part; Avg = average, s.e.d. = standard error of differences, d.f. = degrees of freedom, F pr. = F probability. Varieties are ranked in order of total fibre percentage of the bottom stem part.

Gesamt-Fasergehalte, Gehalte an geschwungener Langfaser und Verhältnisse geschwungene Langfaser : Gesamtfaser für 5 Faserhanfsorten in zwei Sortenversuchen in Jokioinen (FIN, 2004) und Achterberg (NL, 2007). B = unterer, M = mittlerer, T = oberer Stängelabschnitt; Avg =Mittelwert, s.e.d. = Standardfehler der Differenz, d.f. = Freiheitsgrade, F pr. = Irrtumswahrscheinlichkeit. Die Sorten sind sortiert nach Gesamt-Fasergehalt im unteren Stängelabschnitt.

Variety	A. Total fibre (%)			B. Scutched long fibre (%)				C. Ratio (%)		
	Stem part			Stem part				Stem part		
	B	M	Avg	B	M	T	Avg	B	M	Avg
Finland										
Tiborszállási	19.9	23.6	21.7	13.1	21.5	15.6	16.7	66	91	78
Fedora	26.0	30.3	28.2	18.1	27.0	18.4	21.0	69	88	79
Futura	26.7	28.0	27.3	19.8	24.1	16.6	20.1	74	86	80
Bialobrzeskie	32.1	34.2	33.2	25.8	30.1	21.4	25.8	80	88	84
Beniko	38.8	41.7	40.3	31.8	37.1	24.2	30.9	81	88	85
Avg	28.7	31.5	30.1	21.7	28.0	19.2	23.0	74	88	81
The Netherlands										
Tiborszállási	18.8	23.5	21.2	14.7	21.1	17.0	17.6	78	90	84
Fedora	24.5	32.6	28.6	20.2	29.7	25.8	25.2	82	91	86
Futura	25.9	31.1	28.5	23.1	29.0	26.7	26.3	89	93	91
Bialobrzeskie	30.7	37.3	34.0	26.3	33.2	28.0	29.2	86	89	87
Beniko	37.2	40.8	39.0	31.9	37.6	28.6	32.7	86	92	89
Avg	27.4	33.1	30.3	23.2	30.1	25.2	26.2	84	91	88
All										
Tiborszállási	19.4	23.5	21.5	13.9	21.3	16.3	17.2	72	90	81
Fedora	25.3	31.5	28.4	19.1	28.3	22.1	23.2	75	90	83
Futura	26.3	29.5	27.9	21.4	26.5	21.6	23.2	82	90	86
Bialobrzeskie	31.4	35.7	33.6	26.1	31.7	24.7	27.5	83	89	86
Beniko	38.0	41.2	39.6	31.9	37.4	26.4	31.9	85	90	87
Avg	28.1	32.3	30.2	22.5	29.0	22.2	24.6	79	90	84
s.e.d.		0.73								
d.f.		49								
F pr. Site × Variety × Stem part		0.012			n.s.				n.s.	
s.e.d.					0.78					
d.f.					19					
F pr. Site × Variety		0.004			< 0.001				n.s.	
s.e.d.					0.69				1.8	
d.f.					12				11	
F pr. Site × Stem part		< 0.001			< 0.001				< 0.001	
s.e.d.					0.72				2.1	
d.f.					78				50	
F pr. Variety × Stem part		< 0.001			< 0.001				< 0.001	

the stems were cut manually at soil level with pruning shears (no stubble), in Finland the hemp was harvested using a garden tiller with a saw tool, which inevitably created a stubble of a few centimetres (< 5 cm).

WESTERHUIS et al. (2009a) showed that the fibre content of the bottom 5 cm of hemp stems is very low and that the fibre content increases towards the middle of stems. Consequently, cutting the stems a few centimetres higher increases the fibre percentage. This might explain why the differences between bottom and middle part were smaller in Finland than in the Netherlands, and why the fibre percentage in the bottom part on average was a little higher, but only significantly higher in Beniko, in the Finnish hemp.

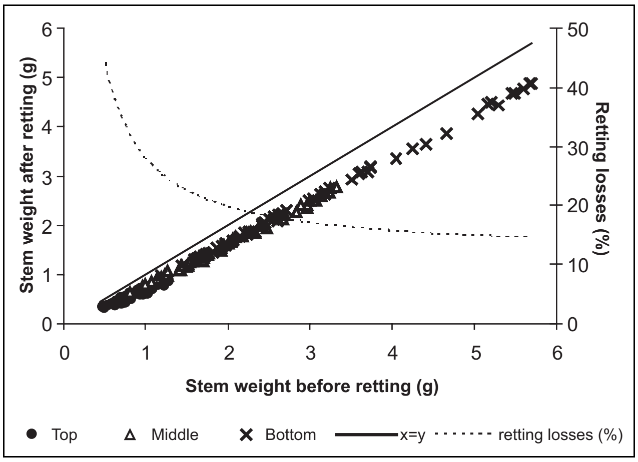

Fig. 4: The stem part weight after retting plotted against the stem part weight before retting for top, middle, and bottom 50 cm stem parts in a fibre hemp experiment in the Netherlands in 2007 (3 harvest times × 5 varieties × 3 stem parts × 4 replicates). The distances between the symbols and the line x = y indicate the absolute retting losses. With increasing stem weight the retting loss percentage decreased.
Gewicht der Stängelabschnitte nach der Röste in Abhängigkeit von ihrem Gewicht vor der Röste für die oberen, mittleren und unteren 50 cm der Stängel aus dem Faserhanf-Experiment den Niederlanden (2007, 3 Erntetermine x 5 Sorten × 3 Stängelabschnitte × 4 Wiederholungen). Die Abstände zwischen den Symbolen und der Winkelhalbierenden geben die Röstverluste an. Mit zunehmendem Stängelgewicht nahmen die relativen Röstverluste ab.

Plant size

For reasons explained above, the five varieties that were grown at both sites were compared with ANOVAs instead of multiple linear regression analyses. It was decided to compare the results of the last harvest time (H3) in the Netherlands with the hemp grown in Finland, because at H3 the stem weight was highest. However, the average stem weight at H3 was still lower than the average stem weight of the Finnish hemp. WESTERHUIS et al. (2009a) showed that with increasing stem weight, the fibre percentage decreased, although the ratio in which fibres and wood were produced did not change (Fig. 3). This effect might have caused the slightly lower total fibre percentages in the middle stem part in Bialobrzeskie, Fedora, and Futura in Finland as compared to the Netherlands.

Scutched long fibre

The second aim of our experiments was to determine whether genotype × environment effects were present for the scutched long fibre percentage. When the five varieties were ranked from low to high scutched long fibre percentage, at both sites the ranking was the same as for the total fibre percentage.

For the scutched long fibre/total fibre ratio, differences between sites and between varieties were only present in the bottom part of stems. In this bottom part, the ratio was lower than in the middle stem part, though differences were not significant for Chamaeleon, Dioica, and Beniko in the Finnish experiment. The lower ratio in the bottom part was expected, because in WESTERHUIS et al. (2009a, b), the bottom 50 cm of stems always showed lower scutched long fibre/total fibre ratios than all other stem parts examined, irrespective of sowing density, variety, sowing date or harvest time. In WESTERHUIS et al. (2009a), this was ascribed to the different composition of the bottom 5 cm of the stems. However, this was based on an experiment with only one variety at one site. The experiments described in this paper showed that the scutched long fibre/total fibre ratio in the bottom part was different for varieties and sites. Possibly this was due to differences in plant height (Tab. 1) and differences between varieties with respect to the length of the middle section (see below), or the interaction between these factors. The data set obtained in this experiment, however, was not suitable to investigate the background of the differences between varieties and sites in more detail.

The scutched long fibre/total fibre ratio in the middle stem part was around 90%, regardless of site or variety. To produce homogeneous, high-quality textile fibres preferentially only this middle part of the stems should be used to extract the fibres (CAPPELLETTO et al. 2001, VAN DAM & VAN DEN OEVER 2006), hence this is the most valuable part. It is therefore very important to know the length of this middle section as related to plant height. The relative weight share of this high-quality stem part should be maximised in order to maximise profits. Upper and lower limits should be known to determine cut heights, and to adjust machinery. In this respect not only the relative long-fibre yield should be taken into account, but also all other important quality aspects that might show patterns along the stem.

In addition, the presence or absence of the unwanted secondary fibres, especially in the bottom part of stems (BÓCSA & KARUS 1998, SCHÄFER & HONERMEIER 2003, AMADUCCI et al. 2005) should be taken into account. Obviously, a homogenous crop, in all aspects, is preferable for such optimisations.

Future research should focus on this, as primary producers need to know the optimal combination of plant height and stem diameter, and the optimal heights to cut the stems at harvest in order to provide the homogeneous high quality raw material the processors require. Stubbles that are too short decrease the quality of the raw materials, stubbles that are too long lower the profits (BREDEMANN 1940).

Retting losses

Whereas large differences were found in the ratio in which varieties produced fibre and wood, variety was an unimportant factor with respect to retting loss percentages. Stem weight before retting accounted for 99.8% of the variance in stem weight after retting (Tab. 2b), which confirms the conclusions of WESTERHUIS et al. (2009b). The differences between varieties, although statistically significant, are in practice unimportant.

Largest variability was found in the top part of the stems (Fig. 4), but the absolute fibre weight in this part is low, as is the fibre quality. These fibres are not suitable for spinning high quality yarns (CAPPELLETTO et al. 2001, VAN DAM & VAN DEN OEVER 2006). Variability in this stem part might also partly be due to the relative low weight of this stem part and structural differences caused by differences in flowering stage (e.g. internode length, branching and the presence of resins).

Crop management strategy

It can be concluded that the effect of the environment on the fibre content of varieties, if any, is small and for practical reasons can be neglected. Differences in fibre content found in literature, given variety, were probably mainly due to differences in retting losses and the processed stem part, and not to differences in the ratio in which any variety produces fibres and wood. With respect to price fixing of unretted hemp stems, it is therefore important to know the variety, and to determine the retting losses under controlled conditions, for which a protocol should be developed that sellers and buyers agree on.

The experiments described in this paper and those in Westerhuis et al. (2009a, b), have shown that the effects of site, sowing density, sowing time and harvest time on the ratio in which any variety produces fibre and wood are absent or minimal. Improving the total fibre content, given variety, is not a promising strategy. To improve the fibre content of a hemp crop at any site, a variety with higher fibre content should be chosen. Crop management, given site, should be focussed on optimising stem dry matter yield and possible other fibre quality traits not studied here. Moreover, the large varietal differences and lack of interactions with the environment shows good prospects for breeding. As genotype × environment interactions are unimportant with respect to fibre content, testing this characteristic on only one site should be conclusive.

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