Industrial Crops and Products 11 (2000) 73–84

INDUSTRIAL CROPS AND PRODUCTS
AN INTERNATIONAL JOURNAL

www.elsevier.com/locate/indcrop

Comparison of bast fibre yield and mechanical fibre properties of hemp (*Cannabis sativa* L.) cultivars

Hannele S. Sankari *

Plant Production Research, Agricultural Research Centre of Finland (MTT), FIN-31600 Jokioinen, Finland

Received 5 July 1999; received in revised form 17 July 1999; accepted 21 September 1999

Abstract

High stem yield and high bast fibre content in stem are generally accepted as important properties for fibre hemp (*Cannabis sativa* L.) Quality demands for fibre used in the new non-woven products have not yet been defined. The Ukrainian monoecious fibre hemp cv. Uso 11 was compared with 13 other fibre hemp cultivars in 1995–1997 in Finland (latitude 60°49′ N). Stem yield, stem length, stem diameter, bast fibre content in stem, bast fibre yield, proportion of primary fibre in the bast fibre and primary fibre yield are reported, as well as breaking tenacity and elongation at break of the fibres. The average stem yield of cv. Uso 11 was 5947 kg dry matter ha^{-1} and only dioecious cvs. Kompolti Hybrid TC and Novosadski produced significantly higher yields. The bast fibre content in the stem of cv. Uso 11 averaged 21.7%, and four other cultivars, both mono- and dioecious ones, had significantly higher content. The proportion of primary fibre in the bast fibre of cv. Uso 11 averaged 91.0%, and cultivars with significantly lower primary fibre fraction were all dioecious. The average bast fibre and primary fibre yields of cv. Uso 11 were 1301 and 1188 kg dry matter ha^{-1}, respectively. Only cv. Kompolti Hybrid TC produced significantly higher bast fibre and primary fibre yields. The median values for breaking tenacity and elongation at break of the fibres varied, depending on experimental year and cultivar, from 41 to 74 cN/tex and from 3.3 to 5.5%, respectively. The dioecious cultivars showed better or equivalent properties to cv. Uso 11. Because the season was too short for seed production, which is a prerequisite for obtaining the EU subsidy, dioecious hemp cultivars cannot be recommended for cultivation in Finland. However, monoecious Ukrainian cvs. Uso 11 and Uso 31 and Polish cvs. Beniko and Bialobrzeskie are suitable for the long-day growth conditions prevailing in Finland.

Keywords: Stem yield; Bast fibre content; Primary and secondary fibre; Breaking tenacity; Elongation at break

1. Introduction

Hemp (*Cannabis sativa* L.) bast fibres traditionally have been used for textile, rope and twine. Recently, numerous other products have been described (Karus, 1995). The bast fibre content in

* Tel.: +358-3-41881; fax: +358-3-41882437.
E-mail address: hannele.sankari@mtt.fi (H.S. Sankari)

PII: S0926-6690(99)00038-2

hemp stem is reported to depend on genotype, plant density and development stage of the hemp at harvest (Höppner and Menge-Hartmann, 1994; van der Werf et al., 1994; Cromack, 1998). Hemp bast fibre consists of primary and secondary fibres, which according to Hoffmann (1961) differ in length of single fibre cells, cell wall thickness, strength and stage of lignification. Primary fibre develops during the phase of rapid stem elongation and consists of large and long fibre cells averaging 20 mm in length. Secondary bast fibre cells are more lignified and shorter, averaging just 2 mm in length.

For the textile industry, the primary fibre bundles are valuable long fibre and the secondary fibre bundles are less valuable tow (Hoffmann, 1961). In paper making, any increase in the secondary bast fibre fraction is probably undesirable (van der Werf et al., 1994). For the new non-woven uses, however, the quality of the hemp fibre has not yet been defined, and it may not be particularly important. Thus, according to van der Werf et al. (1996), the most desirable properties for fibre hemp at the moment are high stem yield and high bast fibre content in stem. Smeder and Liljedahl (1996) concluded that for technical use of flax (*Linum usitatissimum* L.) fibres the most important fibre properties are fibre length, strength, chemical composition and diameter. The same properties probably are important also for technical use of hemp fibres.

Table 1
Fibre hemp cultivars included in the field experiments in the years 1995–1997

Cultivar	Experimental year		
	1995	1996	1997
Beniko (POL)		x	x
Bialobrzeskie (POL)		x	x
Fedora 19 (FRA)		x	x
Felina 34 (FRA)		x	x
Futura 77 (FRA)		x	
Kompolti[a] (HUN)			x
Kompolti Hybrid TC[a] (HUN)	x	x	x
Novosadski[a] (former YOU)		x	x
Secuieni 1 (RUM)		x	
Uniko B[a] (HUN)	x	x	x
Uso 11 (UKR)	x	x	x
Uso 31 (UKR)	x	x	x
V (wild) × T (Tiborszállási)[a] (HUN)			x
V (wild) × Kompolti[a] (HUN)	x		

[a] Dioecious cultivars, others are monoecious.

Ukrainian monoecious cv. Uso 11 has been recommended for cultivation in Finland as an early maturing cultivar with relatively high stem yield (Sankari and Mela, 1998). In this study, cv. Uso 11 was compared with 13 other fibre hemp cultivars originating from various parts of Europe. Besides stem yield, stem length, stem diameter, bast fibre content in stem, proportion of primary fibre in the bast fibre and fibre yield, study was made of breaking tenacity and elongation at break of the fibres, to allow a cultivar recommendation based on both hemp productivity and mechanical fibre properties.

2. Materials and methods

Field experiments with 14 fibre hemp (*C. sativa* L.) cultivars in total (Table 1) were carried out at the Agricultural Research Centre (MTT) in Jokioinen, Finland (latitude 60°49′ N) in the years 1995–1997. The detailed field management for 1995–1996 is described by Sankari and Mela (1998). In 1997, the field experiment was laid out in a randomized complete block design with four blocks. The experiment was on sandy clay and mixed fertilizer was applied before sowing at a rate of 108-18-72 (NPK) kg ha^{-1}. The sowing date was 20 May. Seeding rate was 250 viable seeds m^{-2} and seeds were drilled using an Oyjørd experimental drill with a row width of 12.5 cm. Plot size was 10 × 1.25 m. Cultivars were harvested on 15 September, or for cvs. Bialobrzeskie, Kompolti, Kompolti Hybrid TC, Novosadski, Uniko B and V × T, on 22 September. Owing to the failure at sowing, the plots of cvs. Fedora 19 in the second replicate and Uso 11 in the fourth replicate were discarded.

2.1. Stem yield

An area of 2 m^2 per plot was harvested for the determination of stem yields in 1997. Stems were cut at soil level. Stem yield (kg dry matter ha^{-1})

was determined as described for the years 1995 and 1996 by Sankari and Mela (1998). For purposes of the present study, the stem yields for 1997 and those reported by Sankari and Mela (1998) for 1995 and 1996 were analysed together, but the third replicate in 1995 was excluded because stem yield was needed in the calculation of fibre yield and in that year the fibre content in stem and the proportion of primary fibre in the bast fibre were determined only for stems derived from two replicates.

2.2. Stem length and stem diameter

To determine stem length (cm) and stem diameter (mm), 25 stems of each cultivar and replicate in 1995–1996 (stems cut at 5-cm stubble height) and five stems in 1997 (stems cut at soil level) were randomly chosen from among the stems harvested to determine stem yield. Stem diameter was measured at the mid-point of the stem. In the case of the dioecious cultivars, male and female plants appeared randomly in the samples.

2.3. Total bast fibre content, proportion of primary fibre and fibre yield

A total of five stems were selected for determining the total bast fibre content (%) in stem and the proportion (%) of primary fibre in the bast fibre. Two extra stems were crushed and oven dried at 80°C for 17 h to determine the dry matter content (%) in stem and then the dry fibre content in dry stem. In 1995 and 1996, the stems for these analyses were randomly chosen from among the 25 stems measured for length and diameter (see above), whereas in 1997 all five stems measured for length and diameter in that year were used for determining the total bast fibre content in stem. Additional stems for other analyses in 1997 were randomly chosen from among the stored stems that were harvested for stem yield determination.

The total fibre content in stem was determined by enzyme retting with liquid enzyme SP 249 (Novo Nordisk, Denmark) in a 0.3% enzyme solution (in water) at 30°C for 2 or 3 days (until the fibres easily separated by hand). Retted bast fibres were rinsed with tap water, and pure fibres (‘Reinfasern’; Bredemann, 1922) were obtained by boiling the fibres for 10 min in a 2% NaOH solution. Thereafter an intense jet of water was applied to remove the non-fibrous elements. The fibres were dried naturally at room temperature and subsequently the dry weight of fibres was determined by oven drying at 60°C for 17 h. The bast fibre content (%) in the stem was calculated by dividing the fibre dry weight by the dry weight of the five stems. Bast fibre yield (kg dry matter ha^{-1}) was calculated by multiplying the stem yield (kg dry matter ha^{-1}) by the bast fibre content.

The proportions (%) of primary and secondary fibre in the bast fibre were determined by the method of Menge-Hartmann and Höppner (1995). Unretted stems were halved and pulled behind a revolving slender peg (Bredemann et al., 1961) for separating the bast fibres mechanically from woody core. The two fibre fractions were then separated from each other by hand and separately boiled in 2% NaOH solution for 60 min and rinsed with an intense jet of water. The dry weights of the primary and secondary fibre fractions were determined as described for total bast fibre above, and the primary fibre fraction was expressed as percentage of the dry weight sum of the fractions. This percentage was used to calculate the primary fibre yield (kg dry matter ha^{-1}).

2.4. Breaking tenacity and elongation at break of the fibres

In 1995–1996, 12 stems of each cultivar were randomly selected from one replicate of the stored stems that had been harvested to determine the stem yield. Bast fibre strings ~20 cm in length and 2–3 mm in width were separated by hand from the middle part of the air-dry, unretted stems. Fibre analyses were done at the Tampere University of Technology, Institute of Fiber, Textile and Clothing Science. Fibre strings were first made finer by hand manipulation, and fibre fineness (dtex), breaking tenacity of the fibres (cN/tex) and elongation at break of the fibres (%) were determined.

Fibre fineness (fineness of fibre bundles), which was needed to calculate the breaking tenacity, was measured with a vibroscope (Lenzing, Austria). Breaking tenacity (i.e. breaking force divided by the linear density of the fibres) and elongation at break (i.e. elongation of a test specimen produced by the breaking force) were measured according to standard SFS-EN ISO 5079(E) (ISO 5079, 1995) in the conditioned state using an Alwetron TCT device (Ab Lorenzen and Wettre, Sweden). Gauge length, i.e. the distance between two effective clamping points of the testing device at the beginning of a test, was 20 mm. A constant rate of extension (CRE) of 20 mm min^{-1} was used to stretch the fibres to rupture.

2.5. Statistical methods

The data for the 3 years were analysed together with the MIXED procedure of SAS Statistical Software (SAS Institute Inc., 1992). Before the analyses, the accordance of the data with the assumption of equality of group variances was checked with Box-Cox diagnostic plots (Neter et al., 1996). The normality assumption of errors was assessed by stem and leaf display and by normal probability plot. Stem yield, stem length, stem diameter, bast fibre content in stem, bast fibre yield, proportion of primary fibre in the bast fibre and primary fibre yield were analysed with mixed models. The cultivar was analysed as a fixed effect, while year and replicate nested in years were analysed as random effects.

Cv. Uso 11, which has been recommended for cultivation in Finnish conditions (Sankari and Mela, 1998), was compared with 13 other cultivars, and the ESTIMATE statement of the MIXED procedure was used to produce t-type contrasts and t-type 95% confidence intervals. Differences to be discussed hereafter are always statistically significant when the term significant is used.

Because the fibre samples represented a single replicate only, the data for breaking tenacity and elongation at break of the fibres are shown separately for 1995 and 1996, and the UNIVARIATE procedure of SAS Statistical Software (SAS Institute Inc., 1991) was used to produce for each cultivar the parameters median (middle value measured), 25th percentile (first quartile, i.e. value is greater than 25% of the values to be measured) and 75th percentile (third quartile).

3. Results and discussion

3.1. Stem yield

High stem yield is an important property for obtaining high bast fibre yield. The overall stem yield (lsmean) was 5961 kg dry matter ha^{-1} (S.E.M. 349) with averages of 6203 kg (S.D. 1591) in 1995, 6342 kg (S.D. 1526) in 1996 and 5708 kg (S.D. 1634) in 1997. The difference in stem yield among the cultivars was significant ($F_{13,62} = 3.75$, $P < 0.001$), but only between cv. Uso 11 and the dioecious cvs. Kompolti Hybrid TC and Novosadski, which produced higher stem yield than cv. Uso 11 (Table 2). It is notable that stem yields in this study were rather low in comparison with the hemp stem yields obtained in the UK, which varied between 6300 and 12 900 kg dry matter ha^{-1} (Cromack, 1998).

Besides higher stem yields, Cromack (1998) reported clearly higher stem lengths, with the average varying between 198 and 237 cm depending on seeding rate and year. The plant stands of the present study were always very short, which may explain the low stem yields: the average stem length was 166 cm (S.D. 19) in 1995, 136 cm (S.D. 18) in 1996 and 144 cm (S.D. 19) in 1997 (note that actual stem lengths were longer by 5 cm since plants were cut at 5-cm stubble height in 1995 and 1996). Most of the cultivars did not differ in stem length from cv. Uso 11 (150 cm, S.E.M. 8). Only dioecious cv. V × Kompolti had significantly longer stems (182 cm, S.E.M. 13, $P = 0.022$). Two monoecious cultivars, Felina 34 (128 cm, S.E.M. 8, $P = 0.013$) and Uso 31 (132 cm, S.E.M. 8, $P = 0.032$) had significantly shorter stems than cv. Uso 11. The reasons for the short plant stands and low stem yields obtained in Finnish experiments have been discussed by Sankari and Mela (1998).

Table 2
The effect of cultivar on stem yield, bast fibre yield and primary fibre yield[a]

Cultivar	Stem yield			Bast fibre yield			Primary fibre yield		
	Difference, kg ha^{-1}	Confidence interval	*P*-value	Difference, kg ha^{-1}	Confidence interval	*P*-value	Difference, kg ha^{-1}	Confidence interval	*P*-value
Uso 11	5947 (mean)			1301 (mean)			1188 (mean)		
Beniko	−920	(−2293, 453)	0.19	−57	(−408, 293)	0.75	−52	(−366, 251)	0.73
Bialobrzeskie	83	(−1290, 1456)	0.90	191	(−159, 541)	0.28	205	(−99, 508)	0.18
Fedora 19	−919	(−2350, 513)	0.20	−381	(−747, −16)	0.041	−288	(−605, 28)	0.07
Felina 34	−789	(−2162, 584)	0.26	−366	(−716, −15)	0.041	−315	(−619, −12)	0.042
Futura 77	−742	(−2557, 1072)	0.42	−405	(−868, 58)	0.09	−366	(−766, 34)	0.07
Kompolti[b]	905	(−742, 2551)	0.28	321	(−100, 741)	0.13	169	(−195, 533)	0.36
Kompolti hybrid TC[b]	1384	(109, 2659)	0.034	470	(147, 794)	0.005	288	(8, 568)	0.044
Novosadski[b]	1476	(103, 2850)	0.036	53	(−297, 404)	0.76	108	(−195, 411)	0.48
Secuieni 1	−1736	(−3845, 373)	0.10	−582	(−1211, −44)	0.035	−516	(−984, −48)	0.031
Uniko B[b]	1057	(−218, 2332)	0.10	290	(−33, 614)	0.08	135	(−145, 415)	0.34
Uso 31	−1246	(−2521, 30)	0.06	−103	(−427, 221)	0.53	−97	(−378, 183)	0.49
V × T[b]	905	(−742, 2551)	0.28	212	(−208, 633)	0.32	149	(−215, 513)	0.42
V × Kompolti[b]	737	(−1424, 2897)	0.50	429	(−129, 988)	0.13	147	(−336, 630)	0.55

[a] Means (lsmeans), corresponding 95% confidence intervals for the differences in stem yield, bast fibre yield and primary fibre yield and statistical significance of the difference between cv. Uso 11 and the other hemp cultivars (*P*-values).
[b] Dioecious cultivars, others are monoecious.

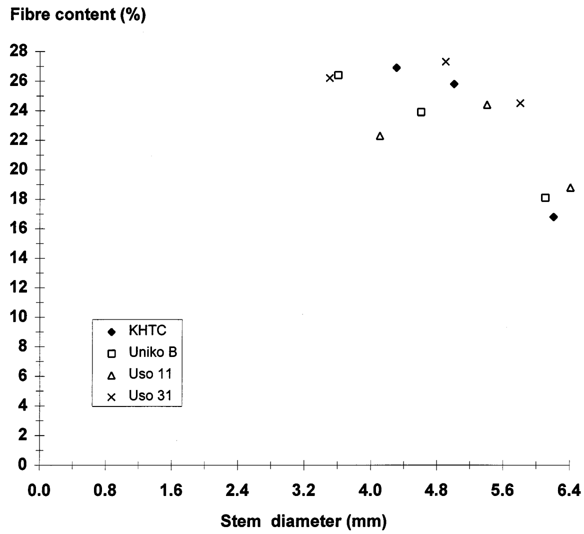

Fig. 1. The relationship between stem diameter and bast fibre content. Symbols represent the yearly (1995–1997) mean values of cvs. Kompolti Hybrid TC (KHTC), Uniko B, Uso 11 and Uso 31.

3.2. Total bast fibre content

Higher bast fibre content in hemp stem has been associated with higher plant density (van der Werf et al., 1996; Cromack, 1998). Stem diameter, which is generally accepted as inversely proportional to plant density, averaged 6.3 mm (S.D. 0.5) in 1995, 5.0 mm (S.D. 0.4) in 1996 and 3.9 mm (S.D. 0.5) in 1997, while plant density (plants per square meter counted at harvest as described by Sankari and Mela (1998)), averaged 57 (S.D. 22), 151 (S.D. 39) and 149 (S.D. 24) in the same years. There was no clear explanation, why the difference in average stem diameter was 1.1 mm less in 1997 than in 1996 although the difference in average plant density was only two plants per square meter. As expected, the bast fibre content in stem was lowest in 1995, averaging 20.1% (S.D. 3.1) and it was higher in 1996 and 1997, averaging 23.8% (S.D. 3.4) and 23.9% (S.D. 3.3), respectively.

Most of the cultivars did not differ significantly in stem diameter from cv. Uso 11 (5.3 mm, S.E.M. 0.6). Significantly thinner stems were produced by cvs. Felina 34 (4.7 mm, S.E.M. 0.6, $P = 0.016$), Uniko B (4.8 mm, S.E.M. 0.6, $P = 0.012$) and Uso 31 (4.7 mm, S.E.M. 0.6, $P = 0.007$). Closer study of the relationship between stem diameter and bast fibre content was made by plotting the yearly mean stem diameter data against the yearly total bast fibre content data for cvs. Kompolti Hybrid TC, Uniko B, Uso 11 and Uso 31. These cultivars were included in the experiment in all 3 years. On the basis of Fig. 1, it could be concluded that bast fibre content in the stem decreases systematically with increasing stem diameter only for dioecious cvs. Kompolti Hybrid TC and Uniko B. From the limited data available, it would seem that the bast fibre content is less sensitive to changes in stem diameter in monoecious cultivars than in dioecious ones.

The overall total bast fibre content in stem averaged 21.9% (S.E.M. 2.0) and the difference among the cultivars was significant ($F_{13,62} = 10.66$, $P < 0.001$). A total of four cultivars had significantly higher bast fibre content than cv. Uso 11 (Table 3). It is notable that the widely cultivated French hemp cultivars produced significantly lower fibre content than cv. Uso 11 (Table 3).

Because of the different methods of analysis or inadequate information about methods employed, the present values of bast fibre content, stem yield, fibre yield and fibre quality cannot meaningfully be compared with those of most other studies. Höppner and Menge-Hartmann (1994) reported higher bast fibre content in the stem of dioecious cv. Kompolti Hybrid TC than monoecious cv. Felina 34: it varied from 19.0 to 25.8% and from 17.4 to 22.8%, respectively. In the present study, the statistical method that was employed allowed comparison of the cultivars only with cv. Uso 11. However, examination of the average bast fibre contents revealed the same tendency between cvs. Kompolti Hybrid TC and Felina 34 as found by Höppner and Menge-Hartmann (1994).

Only one dioecious cv. V × Kompolti exhibited significantly higher bast fibre content than the monoecious cv. Uso 11 (Table 3). The superiority of the dioecious to monoecious cultivars in bast fibre content is not, therefore, an obvious conclusion despite the reports of van der Werf et al. (1994) and Cromack (1998) on this plant character.

3.3. Proportion of primary fibre in the bast fibre

The proportions of primary and secondary fibre in the bast fibre were of interest since secondary fibre has a negative effect on the bast fibre quality in the textile and paper industries (Hoffmann, 1961; van der Werf et al., 1994). Secondary fibre may nevertheless turn out to be an interesting fibre fraction in new non-woven innovations.

The overall mean for the proportion of primary fibre in the bast fibre was 89.0% (S.E.M. 1.9) with yearly means of 85.2% (S.D. 8.3) for 1995, 93.3% (S.D. 6.2) for 1996 and 86.5% for 1997 (S.D. 5.5). The difference (100% minus primary fibre%) gives the percentage of secondary fibre in the bast fibre. Menge-Hartmann and Höppner (1995) reported on microscopic studies where clearly thicker secondary fibre layer in the stem of cv. Kompolti Hybrid TC was found in a rainy year (precipitation between May and September = 381 mm). In the same way, in this study the proportions of primary fibre were lowest in 1995 and 1997, when precipitation between May and September was 371 and 380 mm, respectively. The highest average proportion of primary fibre was found in 1996, when precipitation between May and September was only 286 mm.

The difference among the cultivars in the proportion of primary fibre in the bast fibre was significant ($F_{13,62} = 6.46$, $P < 0.001$). Four dioecious cultivars produced a significantly lower primary fibre content than did cv. Uso 11 (Table 3). Further, the dioecious cv. Novosadski exhibited on average 4.0% higher primary fibre content in comparison with cv. Uso 11, but the difference was not significant. Dioecious cv. V × T and all monoecious cultivars did not differ significantly from cv. Uso 11. In Finnish long-day conditions, female plants of dioecious cultivars rarely started to flower before the harvest (in September or October). Thus, they were not old in the sense of their physiological stage. About half of the plants in stands of dioecious cultivars, i.e. the male plants, flowered and partly even became senescent. According to Hoffmann (1961), male plants form only small amounts of secondary fibres relative to female plants. To discover why the secondary fibre fraction was high in dioecious cultivars and whether it was affected by sex would have required separate analysis of the fibre fractions of male and female plants. Menge-Hartmann and Höppner (1995) reported that the

Table 3
The effect of cultivar on bast fibre content and proportion of primary fibre in total bast fibre[a]

Cultivar	Bast fibre content			Primary fibre content		
	Difference, %	Confidence interval	P-value	Difference, %	Confidence interval	P-value
Uso 11	21.7 (mean)			91.0 (mean)		
Beniko	3.2	(1.0, 5.4)	0.005	−0.4	(−5.0, 4.2)	0.86
Bialobrzeskie	3.0	(0.8, 5.1)	0.008	1.3	(−3.2, 5.9)	0.56
Fedora 19	−3.5	(−5.7, −1.2)	0.003	3.5	(−1.2, 8.3)	0.14
Felina 34	−2.8	(−5.0, −0.7)	0.011	2.4	(−2.1, 7.0)	0.29
Futura 77	−3.5	(−6.4, −0.7)	0.016	1.0	(−5.0, 7.0)	0.74
Kompolti[b]	1.5	(−1.1, 4.1)	0.25	−6.1	(−11.6, −0.6)	0.029
Kompolti hybrid TC[b]	2.0	(0.0, 4.0)	0.052	−7.4	(−11.6, −3.2)	<0.001
Novosadski[b]	−3.7	(−5.9, −1.5)	0.001	4.0	(−0.5, 8.6)	0.08
Secuieni 1	−3.1	(−6.4, 0.2)	0.07	0.9	(−6.2, 7.9)	0.80
Uniko B[b]	1.4	(−0.6, 3.4)	0.16	−8.0	(−12.3, −3.8)	<0.001
Uso 31	3.9	(1.9, 5.9)	<0.001	−0.8	(−5.0, 3.5)	0.72
V × T[b]	0.0	(−2.6, 2.6)	0.99	−2.9	(−8.4, 2.6)	0.30
V × Kompolti[b]	4.3	(0.8, 7.7)	0.016	−16.6	(−23.9, −9.4)	<0.001

[a] Means (lsmeans), corresponding 95% confidence intervals for the differences in bast fibre content and proportion of primary fibre in the bast fibre and statistical significance of the difference between cv. Uso 11 and the other hemp cultivars (P-values).

[b] Dioecious cultivars, others are monoecious.

proportion of primary fibre in the bast fibre of cv. Kompolti Hybrid TC varied between 73.1 and 77.3%. These values are lower than those obtained here (Table 3). Since the secondary fibres are mostly present at the base of stems (Hoffmann, 1961; van der Werf et al., 1995), and in the years 1995 and 1996 of the present study, the primary fibre fraction was determined in stems cut at 5-cm stubble height, the reported primary fibre values were probably higher than they would have been if determined in the whole stem.

3.4. Bast fibre yield and primary fibre yield

The bast fibre yield averaged 1306 kg dry matter ha^{-1} (S.E.M. 165). Yearly means were 1220 kg (S.D. 269) in 1995, 1511 kg (S.D. 424) in 1996 and 1363 kg (S.D. 445) in 1997. The difference in bast fibre yield among the cultivars was significant ($F_{13,62} = 4.39$, $P < 0.001$). Compared with cv. Uso 11, all dioecious cultivars and the monoecious cv. Bialobrzeskie produced on average higher bast fibre yield. However, only bast fibre yield of the dioecious cv. Kompolti Hybrid TC was significantly higher than that of cv. Uso 11 (Table 2). Cromack (1998) has reported on the total bast fibre yields of dioecious cvs. Kompolti and Uniko B, which were higher than those of French cvs. Fedora 19, Felina 34 and Futura 77. The same French cultivars in this study produced even significantly lower bast fibre yield than monoecious cv. Uso 11 (Table 2). This was mainly due to the particularly low fibre content of the French cultivars (Table 3). Cromack (1998) has reported generally higher bast fibre yields in the UK, varying between 1300 and 3500 kg ha^{-1}. The lower fibre yield in Finnish conditions is mainly explained by the lower stem yields.

If only the primary fibre is required, the primary fibre yield ha^{-1} is more important than the total bast fibre yield. A significant difference was found in the primary fibre yield of the cultivars ($F_{13,62} = 3.23$, $P < 0.001$), but again, only cv. Kompolti Hybrid TC produced significantly higher primary fibre yield than cv. Uso 11. Examination of the lower limit of the 95% confidence interval suggested that the difference may be of no consequence in practice even between these two cultivars (Table 2). Cv. Kompolti Hybrid TC had a low proportion of primary fibre in the stem, but owing to its high stem yield the primary fibre yield was also high.

3.5. Breaking tenacity and elongation at break of the fibres

Fibre fineness must be known for calculation of the breaking tenacity of the fibres and it varied from 15.1 to 55.2 dtex in 1995 and from 10.1 to 60.2 dtex in 1996. Fibre fineness depends on the shape and length of single fibre cells, their number in the fibre bundle to be measured, and the processing method (Mäkinen, 1998). In our case, the fibre string samples were made finer by hand manipulation and this contributed to the wide variation in fibre fineness.

The median of the breaking tenacity of the fibres among cultivars varied from 41 to 61 cN/tex in 1995. The line segments in Fig. 2a, that is, the interquartile range of breaking tenacity of the fibres inside of which 50% of the samples were included, indicated that the dioecious cv. Uniko B with shortest line segment had the highest fibre uniformity in 1995. The medians for the breaking tenacity of the fibres were somewhat higher in 1996 than in the previous year, varying between 45 and 74 cN/tex, and the monoecious French cultivars Fedora 19, Felina 34 and Futura 77 showed the highest uniformity of fibres (Fig. 2b). Values of fibre strength have ranged from 48 cN/tex for the unidentified cultivars described by van de Velde et al. (1998) to between 64 and 76 cN/tex for cv. Kompolti Hybrid TC reported by Menge-Hartmann and Höppner (1995). Different treatments of fibre samples before measuring and differences in analytical methods may lead to wide variation in the values of breaking tenacity of the fibres. Furthermore, Fig. 2 reveals a marked variation in the breaking tenacity of the fibres even for a single cultivar.

Elongation at break of the fibres is the elongation of a test specimen produced by the breaking force expressed as percentage of the initial gauge length. The median for the elongation at break of the fibres varied among the cultivars from 3.3 to 5.0% in 1995 (Fig. 3a). Again, fibres of cv. Uniko

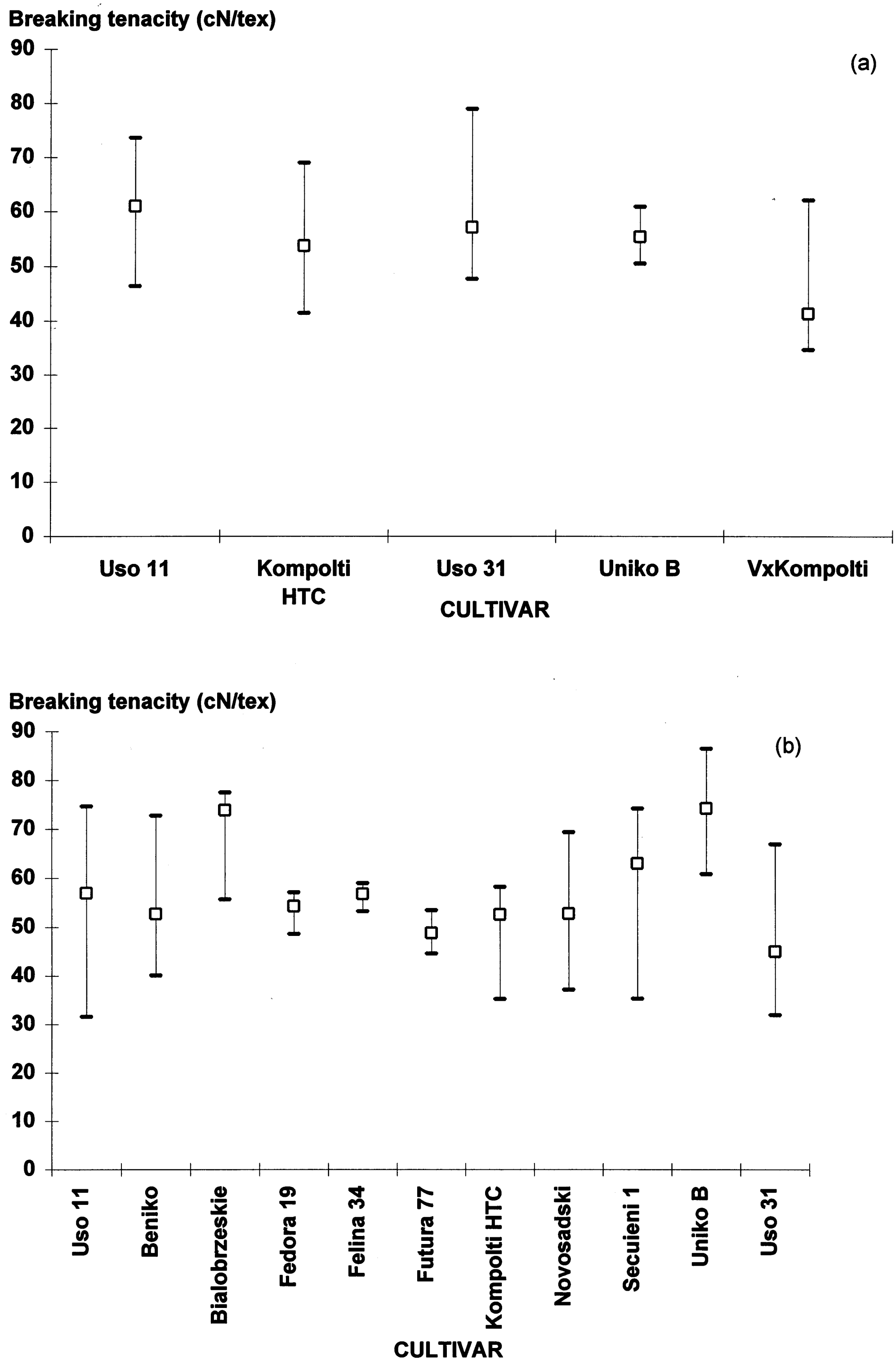

Fig. 2. Median (□), 25th percentile (⊥) and 75th percentile (⊤) for breaking tenacity of the fibres (cN/tex) measured for 12 fibre samples of each cultivar in 1995 (a) and in 1996 (b).

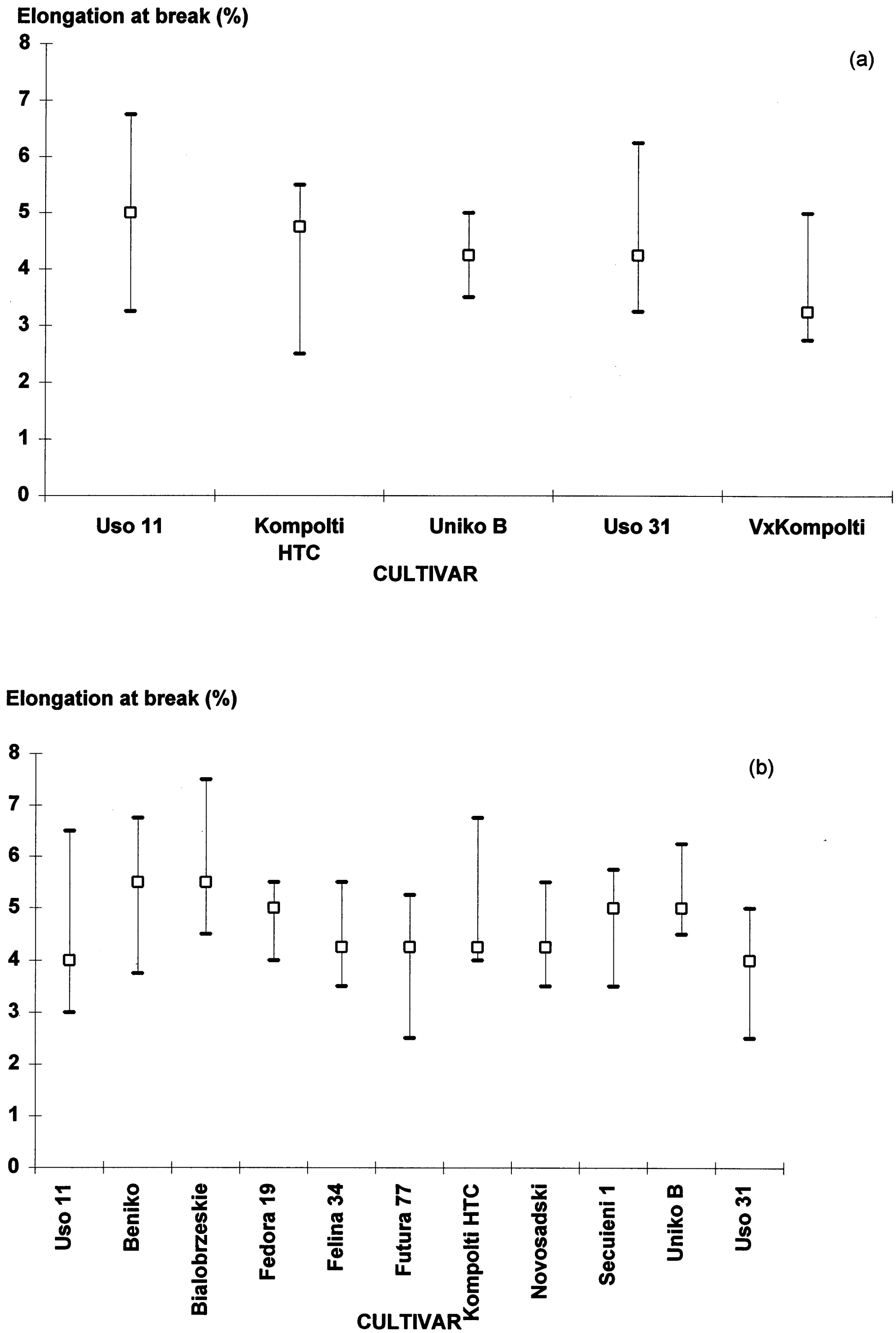

Fig. 3. Median (□), 25th percentile (⊥) and 75th percentile (⊤) for elongation at break of the fibres (%) measured for 12 fibre samples of each cultivar in 1995 (a) and in 1996 (b).

B exhibited the best uniformity. In 1996, the median for the elongation at break of the fibres varied between 4.0 and 5.5% (Fig. 3b). The greatest uniformity in elongation at break of the fibres was found in cvs. Fedora 19 and Uniko B.

An elongation at break value as low as 1.8% has been reported by van de Velde et al. (1998), but comparison with their study is not possible here, since materials and methods used in their study were not announced. Measurements made for single fibres of hemp at Tampere University of Technology have also shown low fibre elasticity, varying from 1 to 3%. However, in the present study, fibre bundles were measured instead of single fibres, and this probably affected the high elongation values (Mäkinen, M., Tampere University of Technology, Institute of Fiber, Textile and Clothing Science, Tampere, Finland, personal communication).

The strengths of the long fibres, tow and even single fibre cells exhibit a wide variation, which, according to Hoffmann (1961), depends on weather during the growing season, soil type, fertilization and retting. Even the fibre cells in a single stem vary widely in strength, with the weakest ones at the base of the stem. Fibres derived from male plants also generally exhibit better strength than female ones (Hoffmann, 1961). Because of the naturally wide variation in breaking tenacity of the fibres in this study, an increase in the number of samples through use of all replicates and the application of statistical models for analysis of the data, would not have revealed any significant differences in breaking tenacities among the cultivars. From the results obtained, it might nevertheless be possible to identify cultivars with more stable fibre quality, less susceptible to experimental management or weather conditions.

4. Conclusions

4.1. Cultivar recommendation for long-day growth conditions

With regard to most of the plant properties studied, the dioecious cultivars exhibited better or equivalent properties for cv. Uso 11. Nevertheless, they do not mature fast enough to produce seeds, and adequate seed production before harvest is the present qualification for hemp subsidy in the EU. Therefore, they cannot be recommended for cultivation in Finland. Sankari and Mela (1998) concluded earlier that cv. Uso 11 is the best cultivar for cultivation in the long-day growth conditions in Finland. If fibre content and fibre yield are considered as well, the earliest maturing monoecious cvs. Uso 31, Bialobrzeskie and Beniko can also be recommended. At present, cvs. Uso 31 and Beniko are included in the fibre hemp cultivar list of the EU.

Acknowledgements

The COST 814 programme provided financial assistance for my work at the Federal Agricultural Research Centre (FAL, Braunschweig, Germany). I wish to thank Dr Ute Menge-Hartmann (FAL) for sharing her knowledge of hemp fibres, Leila Salo for fibre analysis and Kauko Kyläsorri for taking care of the field trials and providing other general assistance.

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