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Industrial hemp (*Cannabis sativa* L.) growing on heavy metal contaminated soil: fibre quality and phytoremediation potential

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Abstract

Hemp (*Cannabis sativa* L.) was used to examine its capability as a renewable resource to decontaminate heavy metal polluted soils. The influence of heavy metals on the fibre quality was of special interest. Determination of heavy metal content was carried out by means of atomic absorption spectroscopy (AAS). Four different parts of the plant were examined: seeds, leaves, fibres and hurds. In each case, the concentration relation was Ni > Pb > Cd. However, the heavy metal accumulation in the different parts of the plant was extremely different. All parts of hemp plants contain heavy metals and this is why their use as a commercially utilisable plant material is limited. We found that the highest concentrations of all examined metals were accumulated in the leaves. In this field trial, hemp showed a phytoremediation potential of 126 g Cd (ha vegetation period)$^{-1}$. We tested the fibre quality by measuring the pure fibre content of the stems and the fibre properties after mechanical separation. In addition, the fibre fineness was examined using airflow systems and image analysis. The strength was measured by testing single fibre bundles with a free clamping distance of 3.2 mm using a universal testing device. Finally, we compared the results from the stems and fibres from trials on heavy metal polluted ground with hemp stems and fibres from non-polluted ground. Since there was no comparable unpolluted area near the polluted one, reference values were taken from an area quite far away and subsequently with a different soil composition and also exposure to different meteorological conditions. Thus, the observed differences are only partially caused by the heavy metal contamination.

Keywords: *Cannabis sativa* L.; Fibre quality; Fibre bundle; strength; fineness; Optical fibre fineness analyzer; Airflow; Phytoremediation; Phytoextraction

1. Introduction

In the future, we will have to deal with the problem that increasing numbers of agriculturally used areas will be contaminated by anthropo-

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genic-derived pollutants. Consequently, these areas will no longer be able to be used for food production. One of the most important classes of pollutants are heavy metals which stem from cadmium-containing phosphate fertilisers, the smelting industry or sewage sludge distribution (Adriano, 1986, Saxena et al., 1999).

However, several approaches exist for cleaning up contaminated soils (Rulkens et al., 1998; Chen et al., 2000). One of the most interesting is phytoremediation, or strictly speaking phytoextraction (Cunningham et al., 1995; Cunningham and Ow, 1996; Ernst, 1996; Chaney et al., 1997; Raskin et al., 1997; Salt et al., 1998; Chen et al., 2000; Meagher, 2000). In this case, plants grow on polluted soil, extract the toxic substances and accumulate them in the upper parts of the plant. They are then harvested, and consequently the soil is cleaned up. On the other hand, the greatest shortcoming of this method is the long period of time needed for decontamination. The plants used in phytoremediation are generally annual herbs which don't have any economic value, but do have a very high extraction potential, namely hyperaccumulators (Robinson et al., 1997; Salt et al., 1998; Wenzel et al., 1999).

The aim of our research is to combine phytoremediation with a crop of commercial interest, with the view of achieving low price decontamination of soil by the production of a commercially usable resource. The plant we chose for our approach was *Cannabis sativa* L., hemp. Hemp has been used by man for over 5000 years and is known to have many uses. The fibres can be used for clothes, insulating material, or as a composite material (Nature, 1996). The seeds serve as an excellent source of oil due to its composition of unsaturated fatty acids (Theimer et al., 1997). The oil has a range of uses including production of colours, lacquer and in the cosmetic industry (Karus et al., 1995; Rausch, 1995; Wirtshafter, 1995; Hupperts et al., 1997). The seeds also provide a source of protein for man and animals (Patel et al., 1994). Moreover, the compounds resulting from hemp's secondary metabolism are of major interest to the pharmaceutical industry (Karus, 1995; Robinson, 1996; Grotenhermen, 1998).

Here, we explore the following issues: (a) is hemp a suitable plant for phytoextraction; (b) is the commercially utilisable fibre material contaminated with heavy metals; and (c) if so, how does this contamination influence fibre quality.

To find out the answers to these issues, we carried out a field trial on a heavy metal contaminated field.

2. Materials and methods

2.1. Plant material/experimental arrangement

The hemp cultivation experiments were organised in 1999 at the trial station in Hagen (Nordrhein-Westfalen, Germany) using the hemp variety *C. sativa* USO 31. The plot of the test was 3×4 m wide, the seed was sown on 12th June. The seed rate was 250 seeds/m^2 (with no additional fertilisation), and the number of plants shortly before harvesting was nearly 100 plants/m^2. The mature plants were harvested about 15 weeks later on 24th September, with an average stem height of 183 cm. The stems were picked by hand, dried and stored at 20 °C and 50% relative humidity. The stems and the separated hemp fibre bundles are named in accordance with the identification code USO Hagen '99. The soil of the trial site had been polluted by sewage sludge distribution and contained 102 ppm cadmium (Cd), 419 ppm nickel (Ni) and 454 ppm lead (Pb) (Hygiene-Institut des Ruhrgebietes, 1997).

We compared the fibre content and the fibre properties from the trials on heavy metal polluted ground with hemp stems from non-polluted ground. Since there was no comparable unpolluted area near the polluted one, reference values were taken from an area with different soil composition and meteorological conditions. Thus, the observed differences are only partially caused by the heavy metal contamination. We took samples from the test location of the chamber of agriculture Weser-Ems in the Wehnen district, in the community of Bad Zwischenahn, near Oldenburg in the northern part of Germany.

The experimental plants were subjected to 4 randomised repetitions. The plots of the test were

3x6 m wide, and were sown also with hemp variety USO 31 during the last week of April, 1999. The seed density was 200 seeds/m^2 with a rate of nitrogen of 100 kg/ha, the germination rate was on average 182 plants/m^2 (28th May). The experimental plot was harvested on 27th August, 1999 and hemp exhibited an average stem height of 260 cm. However, the number of plants reached the level of maturity required for harvesting was much reduced. In 1999, the values of plant density were only examined for the hemp variety Fedrina 74. For this hemp variety, the seed rate was also 200 seeds/m^2 and the number of plants counted shortly before harvesting was 99 plants/m^2. The stems of USO 31 were dried and stored at 20 °C and 50% relative humidity (Martens and Müssig, 2000). The stems and the separated hemp fibre bundles are named in accordance to the identification code USO Wehnen '99.

The stems from both the 'contaminated' trial in Hagen and the 'control' test trial in Wehnen were unretted.

2.2. Mechanical separation of fibre bundles

After crop collection the stems were dried and stored. The fibre bundles were separated mechanically with a BAHMER-FLAKSY laboratory device. This equipment was developed by Bahmer Maschinenbau GmbH (Germany) and consists of four pairs of profiled, rotating rolls. The speed control was adjusted to position 10, resp. 10 m/min transport speed. After six passages through the machine, the hurdless fibre-bundles were refined with a coarse separator. A self-developed laboratory coarse separator was used. This machine consists of a serrated cylinder (Ø 261 mm) and is fed by a rotating roll (Ø 32 mm). The distance from the feeding roll to the rotating serrated cylinder is 20 mm. The fibre transport after coarse separation was organised by air. The results of separation are comparable with industrial separation techniques (Müssig, 2001).

2.3. Chemical separation of fibre

The fibre content (pure fibre content) was examined by the method from Bredemann (1942) after chemical separation in 2% NaOH in an autoclave at 2 bar pressure. From the test plots, a random sample was taken and from this four stems were cut into top, middle, and bottom parts. The pure fibre content was measured for the different sections.

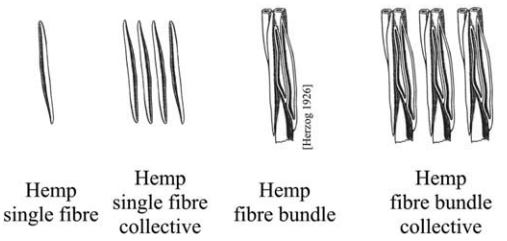

Fig. 1. Various forms of hemp fibres open to testing (Müssig, 2001).

2.4. Tensile testing

The mechanically separated hemp fibres were conditioned for 24 h at 20 °C and 65% relative humidity. The strength of single hemp fibre bundles was tested. Fig. 1 shows the differences between the various forms of hemp fibres which are open to testing.

The single hemp fibre bundles were tested in an Instron universal testing device 4502 with an Instron 2518–806/1 kN power cell. Samples were fastened to a Pressley clamp with Plexiglas jaws. The free clamping length was 3.2 mm and the test speed was 2 mm/min. The device is shown in Fig. 2. The length of each tested single bundle was

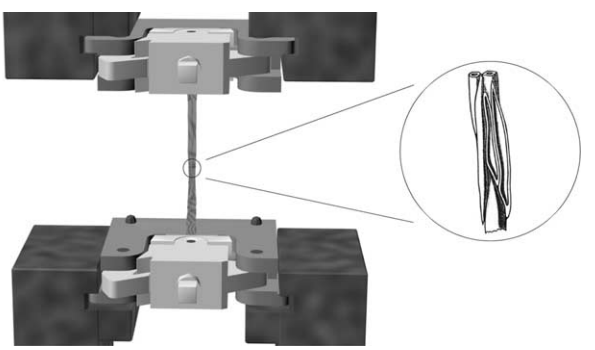

Fig. 2. A single hemp fibre bundle fastened to the Pressley clamp.

constant because of the thickness of the Pressley clamps and the distance of the gauge length (3.2 mm). The length l_B of each bundle was 15 mm. The mass of the single bundles M was measured with an accuracy of 0.01 mg. The mass related fineness gF (in tex) of each bundle could be calculated with the following sizes equation:

$$gF = \frac{\frac{M}{\mathrm{mg}}}{N_B \frac{l_B}{\mathrm{mm}}} \cdot \underbrace{10^{-3} \cdot 10^{6}}_{=1000} \quad (1)$$

With the calculated mass related fineness gF (in tex) and the experimentally measured value for the breaking force of the single bundle F (in N), the strength R_H (in cN/tex) could be calculated according to Eq. (2).

$$R_H \lambda \frac{\frac{F}{\mathrm{N}}}{\frac{gF}{\mathrm{tex}}} \cdot \frac{1}{10} \quad (2)$$

To obtain an acceptable level of accuracy for fibre bundle strength, 100 valid results are necessary. Experiments with bundle breaking inside or near the clamping area or slipping effects were counted as non-valid results.

2.5. Fibre fineness testing

The fineness of fibre bundles was examined by an optical fibre fineness analyzer (OFDA) and airflow methods. The principle of the different measurement methods is given in Fig. 3. The OFDA was developed for measuring the diameter of wool fibre (Baxter et al., 1992). This apparatus efficiently measures width distribution of bast fibre bundles and results have been found to correlate well with those of other methods. Because of the large number of measurements taken, our results could be well reproduced. Compared with the OFDA, the airflow method does not provide information about the distribution of fineness for individual bundles. However, this method is very rapid as well as being highly reproducible (Drieling et al., 1999).

Prior to the experiment the hemp fibres were conditioned for 24 h at 20 °C and 65% relative humidity. The pressure of the Airflow testing device was adjusted to a water column of 120 mm and calibrated after a recently developed method to get comparable airflow values from different labs and researchers for hemp testing (Müssig, 2001). For each sample, we used three specimens each weighing 2.5 g. The measurement was taken three times.

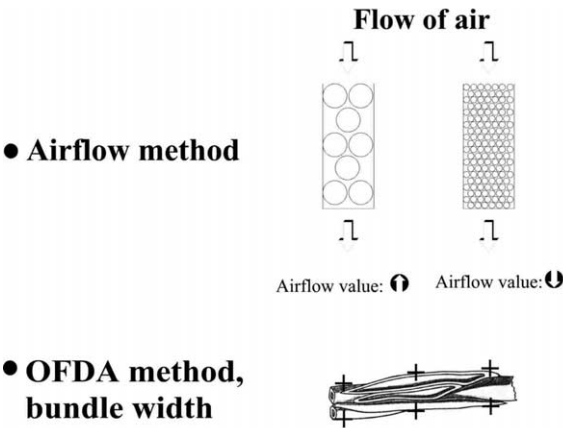

Fig. 3. Airflow and OFDA methods to measure the fineness of hemp fibre bundles (Martens and Müssig, 2000).

The FMT-Shirley device works in the same way as the airflow, i.e. with indirect examination of the fibre surface by the flow of air. The coarse hemp fibre bundles were measured in the FMT at compression stage P_L. For each sample we used three specimens each weighting 4 g. The measurement was taken three times. In contrast to the airflow, coarser fibres gave low and fine fibres high Shirley values.

To examine the bundle width distribution with the OFDA, the bundles were cut into 3 mm long snippets. The snippets were prepared on a slide using tweezers. We prepared 5 slides for each hemp sample for both USO Hagen '99 and USO Wehnen '99. Each slide was scanned twice.

2.6. Determination of heavy metal content

Determination of heavy metal content was carried out by means of atomic absorption spectroscopy (AAS). Four different parts of the plant were prepared as samples: (1) seeds; (2) leaves; (3)

fibres; and (4) hurds. These samples were dried at 105 °C for 3 h prior to the analysis. For each sample, 1.5–2 g were weighed in a 24-ml crucible, and heated to 450 °C at a rate of 2 °C/min, and kept at this temperature for 10 h.

After cooling, the residues were weighed again to obtain the total residue amount, dissolved in 10 ml concentrated nitric acid (HNO_3 ROTIPURAN®, Roth no. 4989.1), and then diluted with distilled water to a total volume of 50 ml.

This solution was used as the sample for AAS determination of cadmium (Cd), lead (Pb) and nickel (Ni) content in an AAS 5FL (Carl Zeiss Technology). Heavy metal content of the original sample was calculated back from the concentration of the measured solution.

3. Results and discussion

3.1. Fibre properties

One problem we faced for this investigation was that we could only use hemp plants from different habitats. Many different factors are known to influence hemp fibre quality and quantity such as meteorological conditions, soil properties, fertilisation, sowing period, plant density and harvest period. Therefore, it is difficult to compare the results from plants of different origins. Nevertheless, the data could provide insight if soil contaminated with heavy metals has a significant impact on fibre properties.

3.1.1. Mechanical separation of fibre

Mechanical extractable fibre content after decortication and mechanical separation was 26% for USO Hagen ’99 and 36% for USO Wehnen ’99.

3.1.2. Chemical separation of fibre/pure fibre content

As described in Section 2.3, we examined the fibre content (pure fibre content) using Bredemann‘s method. The results are shown in Fig. 4. We compared the fibre content from the trials on heavy metal polluted ground (USO Hagen ’99) with hemp stems from non-polluted ground (USO Wehnen ’99).

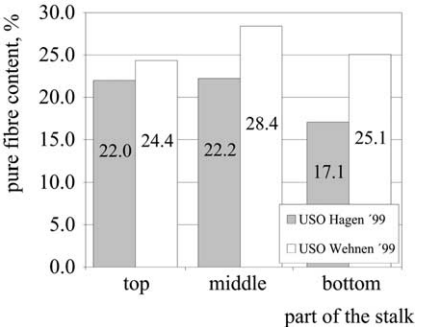

Fig. 4. Pure fibre content of hemp stems/USO Wehnen ’99 vs. USO Hagen ’99.

As seen in Fig. 4, the value of the pure fibre content in the stems of ‘contaminated’ USO Hagen ’99 samples is reduced in comparison to the values of the ‘control’ USO Wehnen ’99 samples. This holds true for all parts of the stems.

Comparable results were achieved by mechanical decortication and separation.

3.1.3. Fibre fineness

We examined the fineness of the mechanically separated hemp fibre bundles using two measurement methods. The Airflow measurements are shown in Fig. 5.

The Airflow values gave highly similar results for both ‘contaminated’ and ‘control’ hemp samples, with a tendency for the USO Wehnen ’99 sample to be a little bit coarser. The same result was observed with the FMT-Shirley values (Fig.

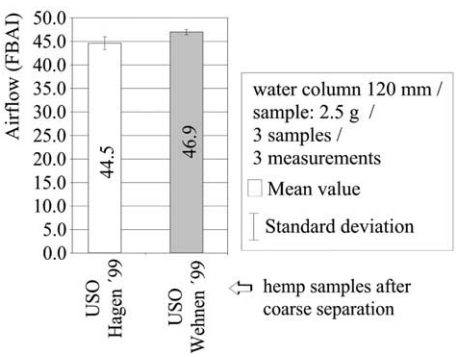

Fig. 5. Airflow values for the fineness of mechanically separated hemp fibre bundles/USO Wehnen ’99 vs. USO Hagen ’99.

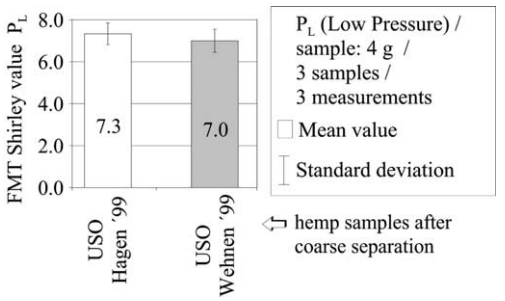

Fig. 6. FMT-Shirley value for hemp fibre bundles/USO Wehnen '99 vs. USO Hagen '99.

6). It should be pointed out that in general coarser fibres show reduced Shirley values.

The results from the airflow and the FMT measurements do not provide information about the distribution of fineness of the bundles. However, these methods are very rapid and highly reproducible. To find out about the distribution of fibre bundle width, we used the OFDA system. This apparatus efficiently measures width distribution of bast fibre bundles. The distribution of the coarse separated fibre bundles for the sample USO Hagen '99 is documented in Fig. 7.

The results of the OFDA measurement show a wide distribution of fibre bundle width. For a mechanically coarse separated unretted hemp sample this is typical (Dreyer and Müssig, 2000). The data of the USO Hagen '99 samples are summarised in the box-and-whisker chart in Fig. 8.

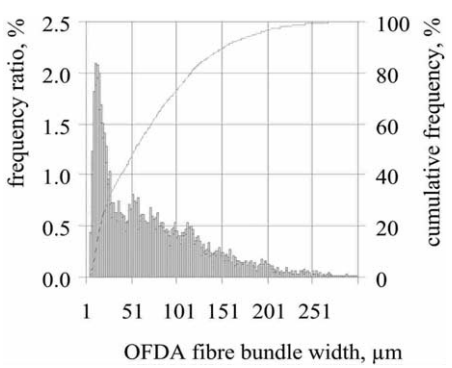

Fig. 7. Distribution of fibre bundle width of hemp USO Hagen '99.

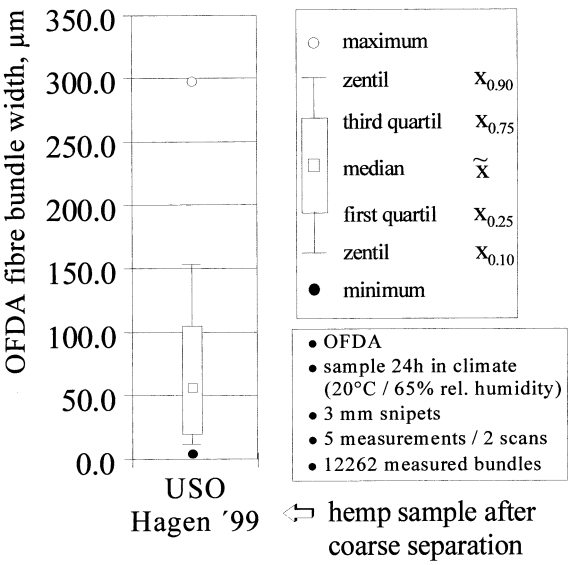

Fig. 8. OFDA fibre bundle width of hemp sample USO Hagen '99.

The nearly identical results from the different fineness testing methods document the low differences between the fineness of the fibre bundles of the two hemp samples USO Hagen '99 and USO Wehnen '99.

3.1.4. Strength of single fibre bundles

As described in Section 2.4, we tested single fibre bundles and not collectives. The tensile properties of the coarse separated hemp fibre bundles are documented in the box-and-whisker chart in Fig. 9.

A wide range of values were obtained, and was more distinct for the single bundles USO Wehnen '99. The wide range of strength distribution of hemp fibres has also been documented in the work of Sankari (2000) and Keller et al. (2001). Although the values of the strength of the fibre bundles of USO Hagen '99 are smaller than those of USO Wehnen '99, the values are still on an acceptably high level and the distribution is more homogeneous.

To summarize the results, heavy metal polluted soil had no significant influence on fibre properties. All results seemed to be in natural occurring range.

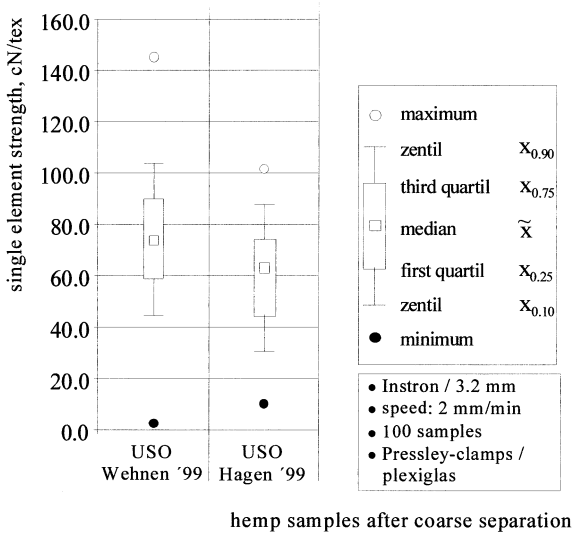

Fig. 9. Strength of single hemp fibre bundles/USO Wehnen '99 vs. USO Hagen '99.

3.2. Determination of heavy metal content

For all samples Cd, Pb and Ni content were examined by AAS. The complete results are displayed in Table 1. Heavy metals could be detected in all parts of the plants which are of commercial interest. In each case, the concentration relation was Ni > Pb > Cd. It is obvious from the data, that hemp shows a strong specificity for the accumulation of various heavy metals. From this study, the concentrations of Cd were eight to 26 times lower than the Ni concentrations. However, when comparing the heavy metal concentrations of the soil with these in the plants, we find that the concentration of Ni in the soil is only four times higher than that of Cd. Therefore, there must be different mechanisms for uptake and accumulation for nickel, lead, and cadmium in general and also for the different plant parts themselves. The highest concentrations of all examined metals were found in the leaves, which indicates the transport of heavy metals via the xylem sap. In the seeds, the concentrations of Cd and Ni are relative high. However, the concentrations found in hurds and fibres are comparably small.

For Ni, the concentration relation was leaves > seeds > hurds > fibres, whereas it was leaves > fibres > hurds > seeds for Pb. For Cd, the relation was leaves > seeds > fibres = hurds, but the Cd concentrations found here are comparably small. Though, the possibility can not be ruled out that concentration levels could be different in soils with a different heavy metal composition.

Another interesting aspect is the total metal uptake of the plant, which depends on (a) the concentrations found in its single parts, and (b) on the relative mass constitution of the plant. That is to say, the contribution of the relatively high metal concentrations found in the seeds to the total mass of metal in the plant is negligible, since the seeds contribute only 8–10% of the plant's total mass (LBP, 1996). The leaf content accounts for 13–15%, fibre content 25–27%, whereas the dominating part is the hurd content with about 60%.

Table 1
Heavy metal contents of the hemp samples

Sample	Weight (g)	Residue (%)	Cd content		Pb content		Ni content	
			ppm	Average	ppm	Average	ppm	Average
Hurds	1.732	2.6	0.78		2.60		12.96	
Hurds	1.973	2.6	0.76	0.8	2.94	2.8	9.99	11.5
Fibres	1.537	3.5	0.85		3.97		7.42	
Fibres	1.575	3.3	0.79	0.8	3.78	3.9	6.32	6.9
Leaves	1.485	23.3	3.94		23.20		63.83	
Leaves	2.058	23.5	2.96	3.5	21.65	22.4	63.46	63.6
Seeds	0.757	6.0	1.19		1.98		33.24	
Seeds	0.829	6.4	1.03	1.1	1.69	1.8	24.79	29.0

These mass contribution may be slightly different depending on variety, season, and crop region, but it depicts clearly that the plant's total metal accumulation is dominated in the hurds on one hand, due to their large contribution of over 50% to the total mass, and in leaves on the other hand due to their high individual metal uptake.

To calculate the phytoextraction potential, we determined the absolute amount of Cd in one plant, i.e. 126 μg Cd (plant)$^{-1}$. By extrapolation the total extraction of Cd by hemp could be calculated as 126 g Cd (ha vegetation period)$^{-1}$. This implies about 126 g Cd (ha)$^{-1}$ in 3–4 months. *Thlaspi caerulescens*, one of the best studied hyperaccumulators for cadmium, is able to accumulate 3000 ppm (Brooks et al., 1998) and to extract up to 2 kg Cd (ha year)$^{-1}$ under optimal growth conditions (Saxena et al., 1999). The phytoextraction potential of *T. caerulescens* is approximately 16-fold higher when compared with USO 31, but hemp grows well under natural conditions, and does not require the expensive use of fertilisers nor the time- and money-consuming control of optimal growth conditions. Another point is, that *T. caerulescens* provides nothing, which could be used as a raw material for commercial purposes.

The question that has be answered is: Could hemp, grown on contaminated soil, be used as a supplier of food or raw material for commercial applications? The WHO (1972) and FAO/WHO (1995) pointed out that 70 μg Cd uptake per day are not harmful to man. The WHO set a limit of 0.1 μg heavy metal (kg food)$^{-1}$. These levels would therefore disqualify hemp seeds or leaves to be used in food production. However, hemp oil could be utilized in lacquer or industrial oil production. The use of hemp fibres for clothes production would not be possible as the heavy metal concentrations exceed the Öko-Tex-Initiative (2000) (Hohenstein), which are 0.1 ppm for Cd, 0.2–1.0 ppm Pb and 1.0–4.0 ppm Ni.

The main use of contaminated fibres and hurds might be in combine material, where the fibre are embedded in polymers and could not be set free.

Another possible use of the plant material is for energy production in thermal power stations, as here the plant material falls below the restrictions (Winkler, 1997). In addition, it might be possible to recycle the metal from the ash, this process is called phytomining (Chaney et al., 1995; Robinson et al., 1997; Brooks et al., 1998; Anderson et al., 1999; Nedelkoska and Doran, 2000). From our work, it seems unrealistic that hemp is an economically viable option in regard to phytomining.

4. Conclusion

The fact that *C. sativa* accumulates heavy metals in all plant parts limits its use as a raw material in clothes as well as in the food chain. However, the high quality of the fibres and hurds, which were not affected by the heavy metal contamination, allows them to be used in special products like combine material. Our experiments provided no evidence of fibre damage due to heavy metal contamination. Fibre bundle fineness and strength from the contaminated as well as the non-contaminated hemp are identical within the limits of experimental error. The fibre content was significantly lower in hemp grown on unpolluted soil, however, it is not possible to decide if this is only an effect of the contamination.

Hemp seems to be best suited for soils with a low content of heavy metals due to its relative low phytoextraction potential. Hemp's commercial aspects together with its ability of extracting heavy metals from the soil makes it an ideal candidate as a profit yielding crop when used for phytoremediation purposes.

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