For applications as solid biofuel, the optimal harvesting period was found to be in spring[35], resulting in an average DM yield of 9.9 Mg ha^{-1}. Even within this harvesting period for solid biofuel production, average DM yields were significantly different between years (*Figure 17*).

3.4 Influence of nitrogen fertilisation

While significant differences in biomass dry matter yield of hemp were found between years for the specific harvesting periods relevant for biogas or solid biofuel, no significant differences were observed between different N fertilisation levels within each trial year (*Figure 17*; **Paper I**).

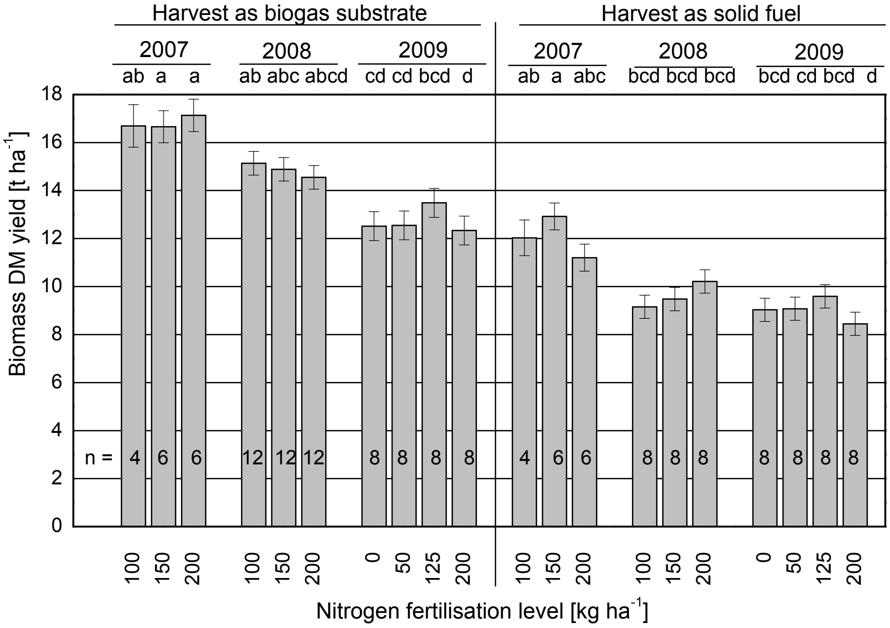

Figure 17. Average dry matter (DM) yield of industrial hemp at harvesting dates relevant for use as biogas substrate (highest DM yield) or solid biofuel (lowest MC content). Different letters indicate significant differences in DM yield for different years and N fertilisation level, separately for biogas and solid biofuel application. Numbers on bars (n) indicate number of samples. Error bars indicate standard error.

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[35] The term 'spring' represents different months in each year (i.e. March-April 2008 February-March 2009 and March-April 2010).

3.5 Energy balance

3.5.1 Energy input

The four base scenarios differed substantially in their relative amount of energy input (*Figure 18*). The energy input in cultivation was found to be 10.8 and 10.4 GJ ha^{-1} for baled and briquetted solid biofuel production from spring-harvested hemp, respectively, and 7.4 GJ ha^{-1} for autumn-harvested, ensiled hemp biomass for biogas production (*Figure 18*; **Paper IV**).

After intermediate storage, processing of the stored biomass requires energy inputs for conversion and additional transport. Conversion energy requirements differed substantially between the scenarios: inputs were low for solid biofuel combustion in the form of briquetted biomass (0.8 GJ ha^{-1}) and for CHP production from bales (1.5 GJ ha^{-1}) (*Figure 18*). CHP production from biogas was more energy-intensive (2.8 GJ ha^{-1}). The most energy-demanding conversion was the production of vehicle fuel (14.1 GJ ha^{-1}), where upgrading of the biogas to 97% methane content represented 45% of the total energy input. This reflects in the high amount of electricity required for scrubbing and compression of the biogas (*Figure 18*).

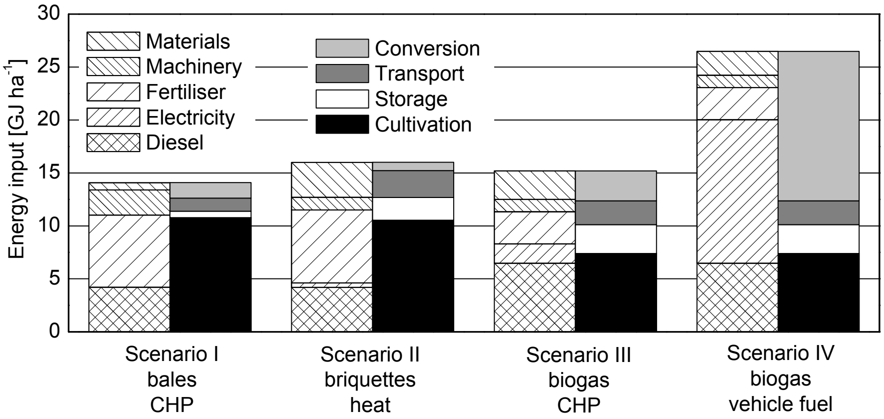

Figure 18. Energy inputs according to production means (left part of columns) and process stage (right part of columns) for scenarios I to IV.

3.5.2 Energy output

For CHP production from solid biofuel, approx. 23 and 41% of the energy contained in the biomass in the field was made available as useful power and heat, respectively (Scenario I, *Figure 19*). Heat production from hemp briquettes resulted in approx. 55% of the energy being made available as useful heat (Scenario II, *Figure 19*).

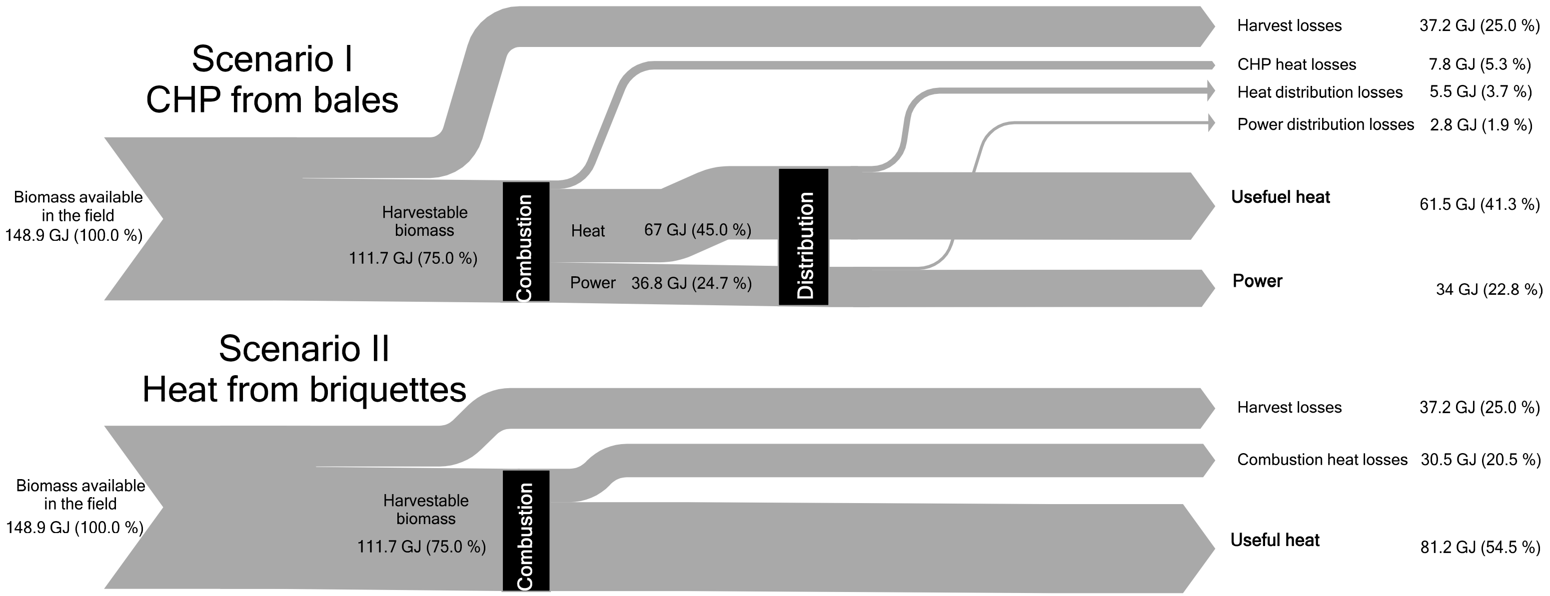

Figure 19. Energy flow diagram accounting for losses and process inefficiencies in the production of CHP from hemp bales (Scenario I, top) and heat from briquettes (Scenario II, bottom).

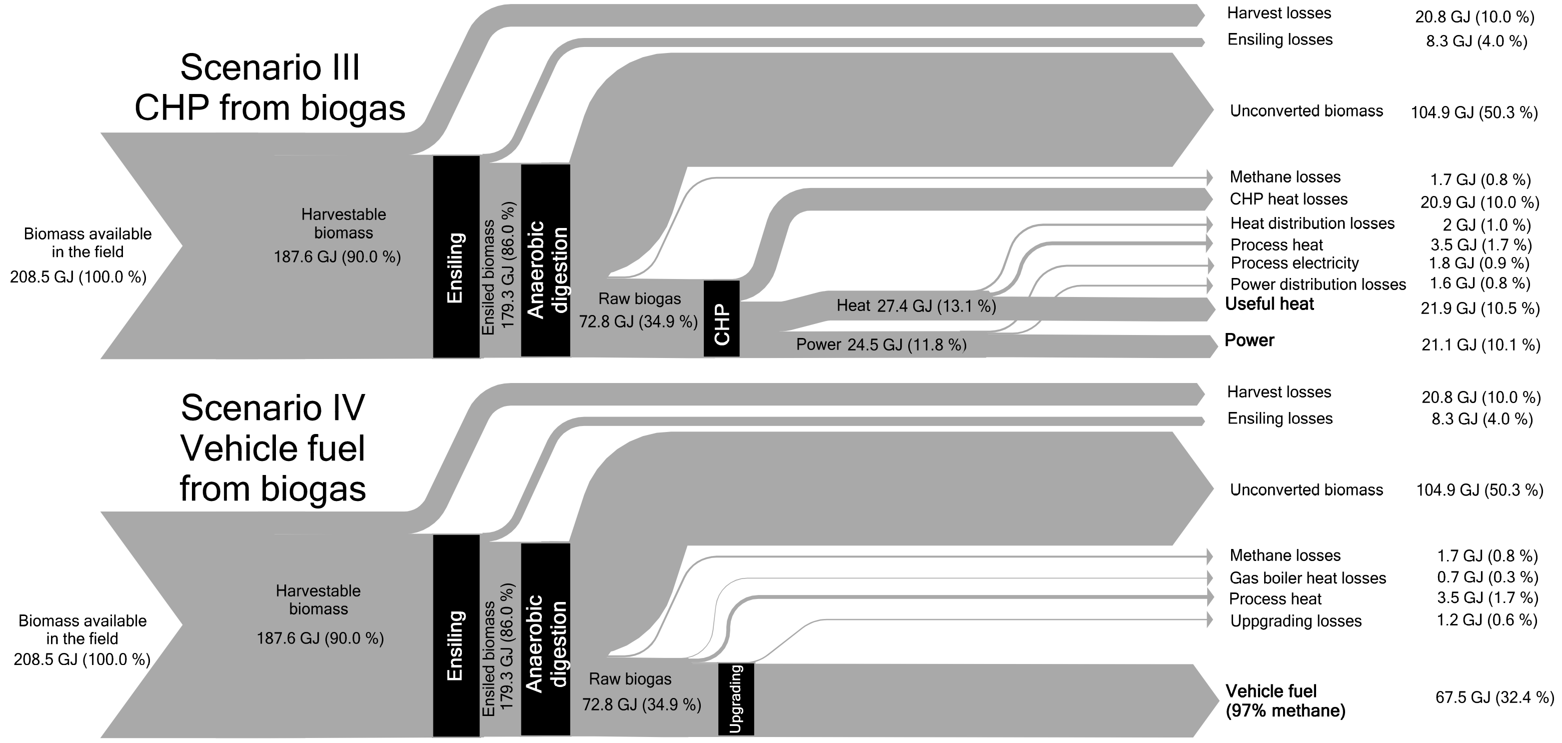

Figure 20. Energy flow diagram accounting for losses and process inefficiencies in the production of CHP (top) and vehicle fuel (bottom) from hemp-derived biogas.

For CHP production from biogas, only 10 and 11% of the biomass energy originally available in the field was made available as useful power and heat, respectively (Scenario III; *Figure 20*). Production of vehicle fuel (97% methane) from biogas resulted in approx. 68% of the energy being conserved in the energy carrier (Scenario IV, *Figure 20*)

3.5.3 Net energy yield

The net energy yield (NEY) per hectare was highest for CHP production from bales and heat from briquettes with 81 and 65 GJ ha^{-1}, respectively (*Figure 21*; **Paper IV**). Overall, conversion efficiencies for these pathways were high (86 and 80%, respectively) as were the output-to-input ratios ($R_{O/I}$ of 6.8 and 5.1, respectively). The NEY of biogas CHP and vehicle fuel production was substantially lower, 24 and 42 GJ ha^{-1}, respectively. Conversion efficiency was 38% for upgraded biogas (vehicle fuel) and 21% for biogas CHP. Both scenarios had $R_{O/I}$ = 2.6.

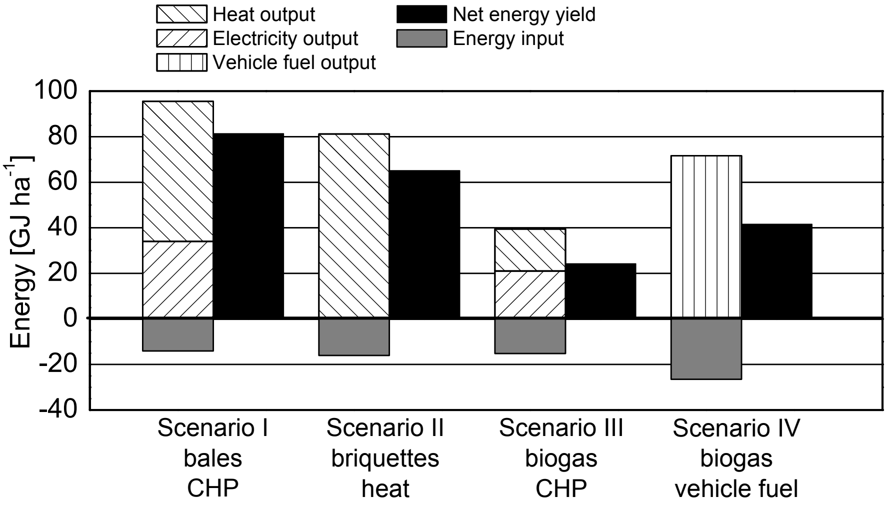

Figure 21. Energy output (white), energy inputs (grey) and resulting net energy yields (black) for scenarios I to IV. Output energy shows heat, power and vehicle fuel production from hemp biomass.

For each tonne DM increase in biomass yield, NEY increased by 15.7, 13.1, 3.9 and 5.8 GJ ha^{-1} for scenarios I to IV, respectively (*Figure 22*, top). *Figure 22*, bottom, shows the influence of hemp biomass DM yield on $R_{O/I}$ for each scenario. The two solid biofuel scenarios were strongly yield-dependent, while the two biogas scenarios were far less sensitive to changes in biomass DM yield.

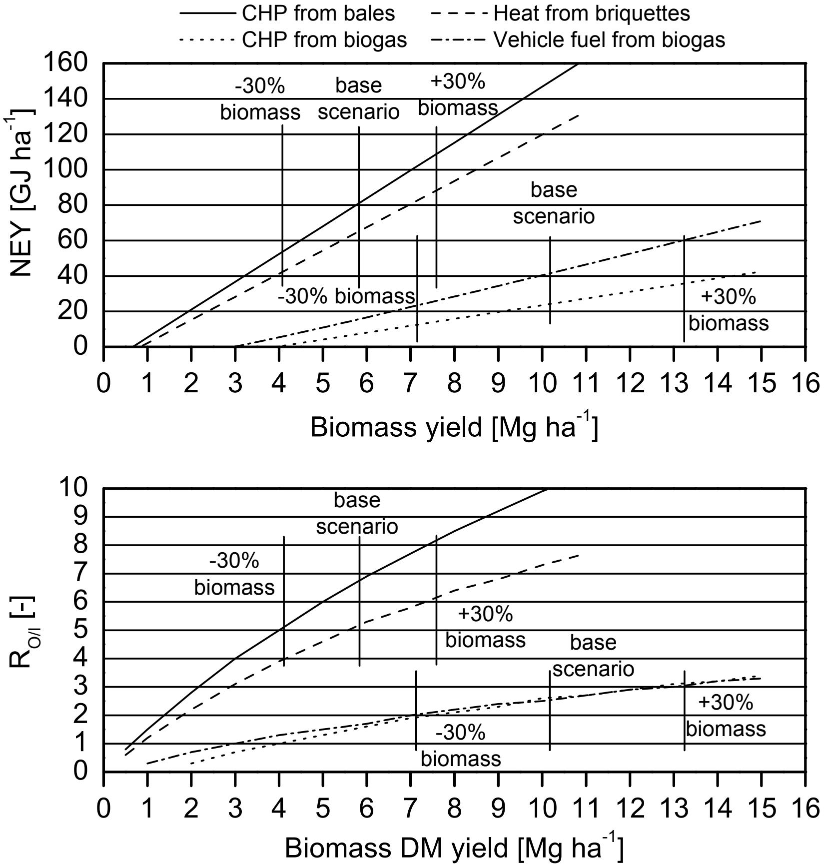

Figure 22. Net energy yield (NEY; top) and energy output-to-input ratio ($R_{O/I}$; bottom) as influenced by the adjusted biomass DM yield of hemp.

4 General discussion

4.1 Hemp cultivation

4.1.1 Influence of high latitudes on hemp biomass yield

Hemp may be a suitable energy crop at high latitudes in general. The hemp cultivar Futura 75 used in the studies of this thesis is medium to late-maturing[36], a trait believed to lengthen the growing period and therefore to increase the biomass yield, since little biomass increase can be expected after flowering (van der Werf *et al.*, 1996; van der Werf *et al.*, 1995). Flowering of hemp is reported to require roughly a maximum day length of 14 hours (Lisson *et al.*, 2000; Borthwick & Scully, 1954). This limit is reached at the southern study site in the beginning of September (Giesen, 2010), which coincides with the maximum biomass DM yields in all three years (**Paper I**). At even higher latitudes (e.g. >60°N) the limit is reached two to three weeks later, prolonging the growing period. However, the growing season for hemp at such latitudes is often 1-2 months shorter in comparison with southern Sweden. Nonetheless, earlier studies have shown that hemp can also give a relatively high biomass yield at latitudes >60°N, e.g. in northern Sweden (Finell *et al.*, 2006; Sundberg & Westlin, 2005) and in Finland (Pahkala *et al.*, 2008), that are only approx. 10-35% lower than those in southern Sweden.

4.1.2 Influence of nitrogen fertilisation on hemp biomass yield

Field trials in southern Sweden from this study indicate that there is scope to reduce N fertiliser levels while maintaining high DM yields. Similar findings

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[36] Maturation represents preparations of the plants for reproduction, i.e. flowering and subsequent seed production.

of high hemp biomass yields on low fertilised plots were reported earlier (Scholz *et al.*, 2001).

Nitrogen fertilisation is applied in crop cultivation in order to increase yields of biomass or protein compounds. Despite large intervals for nitrogen applications, no significant increase in DM yield due to N fertilisation was found for harvesting dates relevant for biogas or solid biofuel production from hemp (**Paper I**). This indicates that nitrogen was not the growth-limiting factor in this study. Similarly, a previous study found no DM yield differences between plots fertilised with N at 80, 160 and 240 kg ha^{-1}, whereas unfertilised plots had a significantly lower DM yield (Iványi & Izsáki, 2007).

4.1.3 Annual variation of the hemp biomass yield

Although significant, the differences in DM yields for hemp between years found in the field trials of this thesis were within the normal variation range for crops (Porter & Semenov, 2005).

Biomass yields often vary with the weather conditions during cultivation. Major parameters influencing biomass yield are accumulated temperature and precipitation, which are dependent on e.g. geographic location and sowing date. Differences in sowing date in the field trials led to differences in accumulated temperature and precipitation. These parameters can partly explain the yield differences found, which is confirmed by findings from earlier studies, where later sowing dates resulted in lower DM yields in the magnitude of 3-4 Mg ha^{-1} for one month of delay (Rice, 2008; Crowley, 2001; van der Werf *et al.*, 1996; van der Werf, 1994).

4.2 Hemp energy yields

4.2.1 Biomass energy yield

Autumn-harvested hemp has a biomass energy yield (BEY) similar to that of other high-yielding biogas crops, including maize and sugar beets (*Figure 23a*; **Paper I**). For biogas production, a combination of high BEY per hectare and high specific methane yield is crucial for the competitiveness of an energy crop. Maize being a high-yielding competitor is the main substrate for biogas production in Germany. Sugar beets are currently discussed as biogas substrate, e.g. in Germany, but so far only used to a limited extent. Furthermore, sugar beet tops are usually not recovered, although interesting as a biogas substrate.

Spring-harvested hemp has a BEY approx. twice that of wheat straw and similar to that of spring-harvested reed canary grass (*Figure 23b*). Cereal straw is a by-product from food and feed production and competes with hemp as solid biofuel despite its low yield per hectare. Using cereal grains as solid biofuel is ethically disputed and therefore usually limited to batches unfit for food and feed production. Similar to hemp, reed canary grass is a relatively new energy crop in northern Europe, used for solid biofuel production only to a limited extent. Willow grown in a short-rotation coppice (SRC) exceeds the energy potential of hemp by approx. 50% (*Figure 23b*). Regarding biomass energy yield per hectare, hemp is therefore competitive to most common and new energy crops in northern Europe.

The BEY represents the potential energy yield from biomass. As a second step, evaluation of the potential yield of useful energy from biomass conversion is needed.

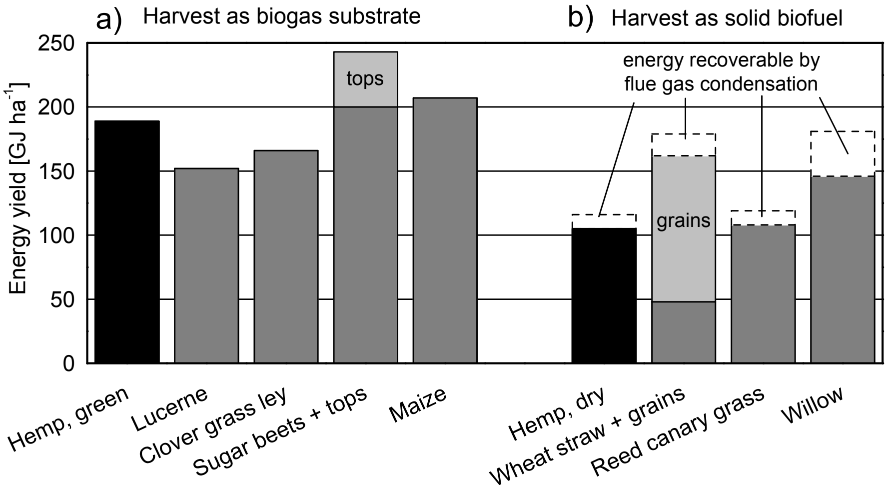

Figure 23. Comparison of annual biomass energy yields for hemp and other agricultural biomass feedstock used as (a) biogas substrate or (b) solid biofuel, respectively. The black bars show data from the present study for hemp, based on DM yields adjusted for average soils in the studied region in southern Sweden. Other data were calculated from standard biomass DM yields for the study area (SCB, 2009) and the corresponding HHV (Amon *et al.*, 2004; Börjesson, 1996) or LHV (Börjesson, 1996; Helsel & Wedin, 1983) for use as biogas substrate and solid biofuel, respectively. The light grey bars show additional biomass energy yield of sugar beet tops and wheat grains. Dashed white bars show maximum additional energy as calculated from the DM yield and the corresponding HHV, which is available if biomass is dried or if flue gas energy can be utilised.

4.2.2 Energy yields for hemp as a biogas substrate

Autumn-harvested hemp can be converted to biogas with high energy yields per hectare, resulting in production of methane, a high-quality vehicle fuel. The methane energy yield (MEY) per hectare of hemp exceeded that of DME from willow, ethanol from wheat grain and biodiesel from rapeseed considerably

(*Figure 24*; **Paper II**). In first generation biofuels for transportation, only the energy-rich plant parts are used for biofuel production, e.g. wheat grains for ethanol and rapeseed for FAME production. In contrast, biogas production from lignocellulosic crops such as hemp and maize uses the whole crop, which explains the relatively high fuel energy yields per hectare of these alternatives.

Hemp had a methane energy yield slightly less than that of maize and sugar beet (*Figure 24*; **Paper II**). Although yielding less methane energy, the relatively new energy crop hemp has a potential that is used only to a limited extent. This reflects in a low energy conversion efficiency for hemp of only 47%, while that of maize and sugar beet is around 70% (*Figure 24*).

The conversion degree is proportional to the specific methane yield, which is high for the main carbohydrates (cellulose and hemicellulose) and low for lignin. The high carbohydrate content and relatively low lignin content of hemp biomass were unaffected by the growth stage (i.e. the corresponding harvest date) of hemp. This indicates promising potential for increasing the MEY, independent of harvest date, by improving digestibility of hemp, e.g. by pretreatment of the biomass (Sun & Cheng, 2002; **Paper III**). Promising results have been demonstrated for steam explosion of hemp (Kreuger *et al.*, 2011b) and other lignocellulosic feedstock such as wheat and oat straw for bioethanol production (Dererie *et al.*, 2011; Erdei *et al.*, 2010).

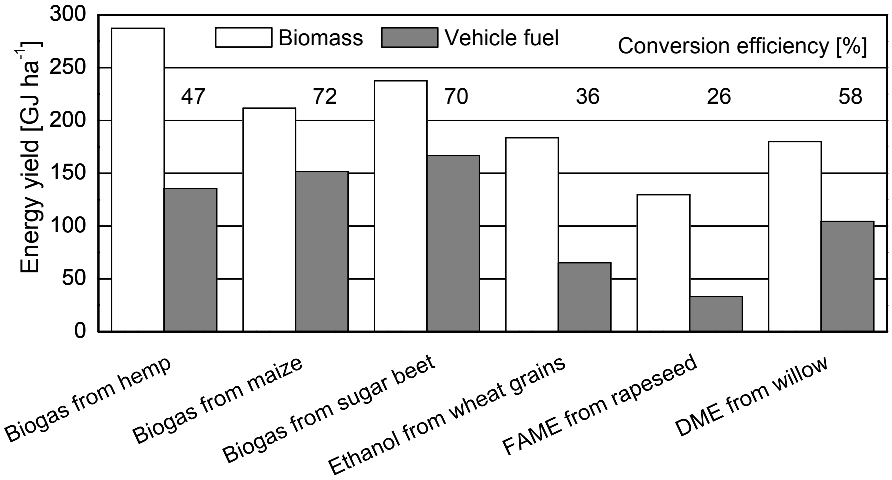

Figure 24. Comparison of the annual energy yields for biogas from hemp (this study) with reference values for other renewable transportation fuels from crops cultivated in southern Sweden (Agriwise, 2009; Schittenhelm, 2008; Börjesson, 2007). White columns depict the energy content of the biomass produced, calculated from the whole-crop DM yield and the corresponding HHV. Grey columns depict the energy yield of the transportation fuel produced, calculated from the DM yield of the plant part used (e.g. grains, seeds) and the corresponding HHV. Numbers above columns represent conversion efficiency in percent. FAME = fatty acid methyl ester for use as biodiesel. DME = dimethyl ether.

4.2.3 Energy yields for hemp as a solid biofuel

The combustion energy yield (CEY) for autumn-harvested hemp was previously reported to be between 135 and 170 GJ ha^{-1} (Scholz *et al.*, 2001), which was confirmed in the present study. The average CEY of 201 GJ ha^{-1} in 2007 in the present study was exceptionally high due to higher DM yields than in 2008 and 2009, indicating the potential to increase average energy yields by further cultivation improvements.

If latent heat from water vaporisation in combustion is not utilised, approx. 8-12% less energy[37] can be yielded from hemp. Therefore, a low MC is favourable for this application, as the MC influences the energy yield as expressed by the LHV of the material. For hemp, the MC decreases with later harvesting date, increasing the energy yield. In parallel, biomass is lost, e.g. by leaf senescence, decreasing the energy yield. The two factors counterbalance each other, leading to the unchanged energy yield per hectare between September and April. This finding needs to be confirmed for other locations and years. However, the general trends in MC and DM yield during the study period indicate a degree of independence of the CEY from the harvesting date. This leaves space for optimising the harvesting date according to other parameters, e.g. storage[38] of the biomass, machinery availability and the chemical combustion properties.

As a third step, evaluation of the realistic yield of useful energy from biomass conversion is needed.

4.2.4 Net energy yield

Hemp has high net energy yields (NEY) similar or higher than that of most other high-yielding energy crops common in northern Europe (*Figure 25*; **Paper IV**). The biomass DM yield per hectare of hemp in the base scenario is rather conservative. Furthermore, hemp is a relatively new energy crop with great potential for yield improvements, e.g. on good soils. Yields approx. 30% above the base scenario (3-year average) for both autumn and spring harvest have been reported on good soils in this study (**Paper I**). Therefore, in addition to the base scenario, an alternative scenario with a 30% higher biomass DM yield for hemp is shown (*Figure 25*).

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[37] Corresponding to moisture contents (MC) between 10-30%.

[38] For storage, MC<30% is desirable to avoid losses due to microbial degradation (Festenstein *et al.*, 1965).

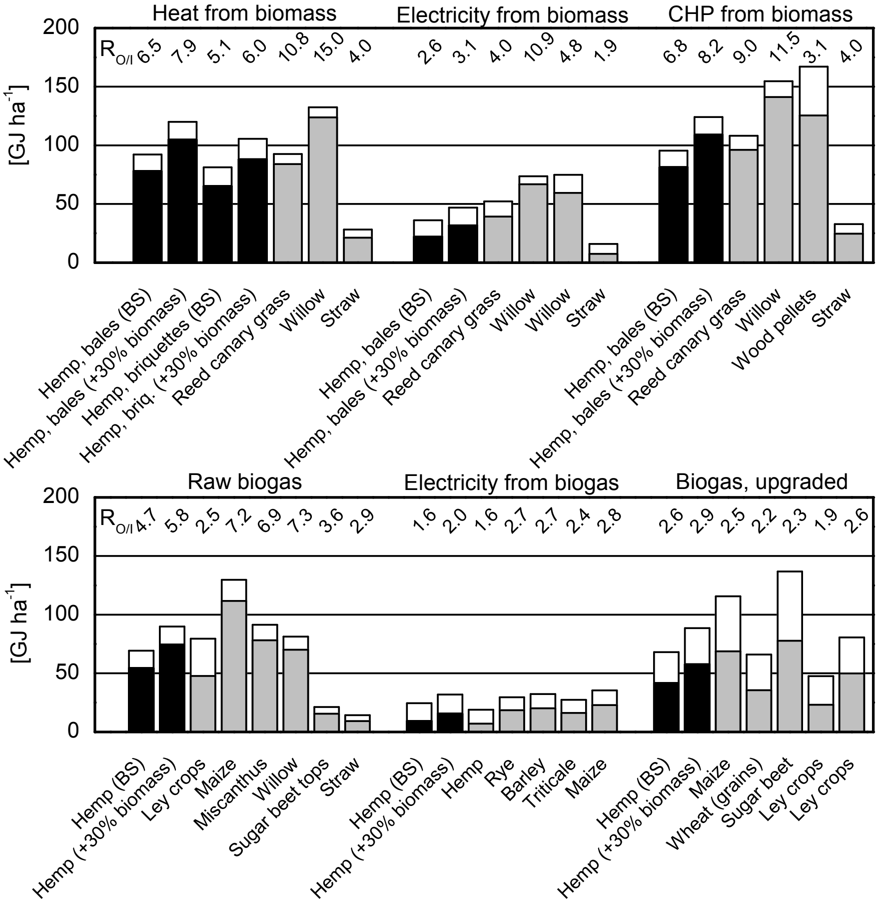

Figure 25. Net energy yield for heat, electricity and CHP from biomass (top) and raw biogas, electricity from biogas and upgraded biogas (bottom). Black columns denote data for hemp from the present study, both the base scenario (BS) and the alternative scenario with +30% biomass. Grey columns denote individual results from published data. The white part of the columns indicates the corresponding energy input. The corresponding output-to-input ratio ($R_{O/I}$) is shown above each column. References: (Börjesson *et al.*, 2010; Caserini *et al.*, 2010; Plöchl *et al.*, 2009; Uellendahl *et al.*, 2008; Berglund & Börjesson, 2006; Hagström, 2006; Heller *et al.*, 2003).

Hemp has similar heat and CHP production to reed canary grass (*Figure 25*, top). Production of electricity only, i.e. not CHP, from hemp is relatively inefficient with $R_{O/I}$ only 2.6 (*Figure 25*, top). Willow exceeds heat and CHP production of hemp significantly. Even if the NEY of willow were recalculated for a comparable electric efficiency (Hagström, 2006) and a comparable biomass DM yield (Heller *et al.*, 2003) as in the present study, it would still be about twice that of hemp (not shown).

Production of raw biogas from hemp has similar NEY to that of ley crops, while maize has about twice the NEY of hemp (*Figure 25*, bottom), mostly due to higher specific methane yield (Uellendahl *et al.*, 2008). These results are reflected again in electricity and vehicle fuel production from biogas (upgraded) for these crops. Miscanthus and willow grown in Denmark and southern Sweden have a higher biomass yield, while their methane potential is similar to that of hemp (not shown), resulting in considerably higher NEY (*Figure 25*, bottom). With a 30% increase in biomass yield, hemp has a similar NEY to miscanthus and willow, while maize still has 50% higher NEY.

Generally for all biomass sources, electricity production from biogas has a relatively low NEY due to the double conversion of biomass to biogas and biogas to electricity. The NEY could be improved if the heat from power generation were used for heating purposes, i.e. in residential or commercial heating by employing combined heat and power (CHP) production. Hemp in the present study had similar NEY to triticale and considerably lower NEY than rye, barley and maize (*Figure 25*, bottom). However, a lower NEY due to lower energy output was reported earlier for hemp (Plöchl *et al.*, 2009).

For the production of upgraded biogas, sugar beet has a substantially higher NEY than hemp, mainly due to much higher methane potential. However, since the energy inputs for utilisation of sugar beet are substantially higher than for hemp, the $R_{O/I}$ is similar to that of hemp.

Comparison of the data from the present study with data from other studies also shows that the production and conversion models employed for calculating the energy balance can differ substantially, the two most variable parameters being the biomass DM yield (e.g. due to fertilisation, weather and soil conditions) and the conversion efficiency (e.g. due to methane potential, thermal/electrical efficiency of the technology of choice). For example, in the literature it is often unclear whether dry matter yields are based on experimental data or data from commercial production, i.e. accounting for field and harvest losses. A comparison of this kind therefore needs to bear in mind the variability of assumptions upon which the scenarios investigated are based.

4.3 Suitability of hemp as biogas substrate

4.3.1 Harvest period

The results indicate that the optimal harvesting period is several weeks long, which may be of practical importance when the availability of harvesting machinery is limited. The specific methane yield was not found to be significantly different between the different harvest dates studied (**Paper II)**. The highest methane energy yield per unit area can therefore be expected when

DM yield is highest, i.e. from September to October (**Paper I**). This harvest period coincides with the period in which the highest DM yields were reported for hemp used for fibre production (Mediavilla *et al.*, 2001). The significant decrease in DM yield from September to October in one year of the study showed that potential extension of this harvesting period is likely to be dependent on the prevailing growing and weather conditions. Earlier harvesting is likely to result in decreased DM yield due to interruption of growth, while later harvesting is likely to result in biomass loss due to senescence.

4.3.2 Substrate handling

Hemp biomass can be ensiled for medium to long-term storage, as is required when a biogas plant is to be supplied with substrate outside the harvesting period. Hemp biomass MC of approx. 60-75% at harvesting is favourable for biogas production. Furthermore, with a MC within this range, the least DM losses are to be expected during ensiling (McDonald *et al.*, 1991). Still, these losses can be significant (Heiermann *et al.*, 2009). Although ensiling is likely to lead to losses of biogas potential, the digestibility and therefore methane content in the biogas have been found to increase in ensiled hemp biomass (Heiermann *et al.*, 2009). However, these findings of increased methane potential in ensiled biomass are not undisputed. Only recently it was reported that many studies reporting methane potentials for ensiled biomass used methods for determining the moisture content of the biomass samples that underestimated the dry matter content of the samples investigated (Kreuger *et al.*, 2011a). This led on to an overestimation of the methane potential and for a number of substrates no significant difference in methane potential was found between fresh and ensiled biomass.

4.4 Suitability of hemp as solid biofuel

4.4.1 Ash properties

Ash properties in spring-harvested hemp are substantially better than in autumn-harvested hemp. Delaying harvest of hemp until spring decreased chlorine levels in the biomass to a level which indicates that the risk for chlorine-aided alkali-fouling is low (Baxter *et al.*, 1998). The S/Cl ratio was above 2 for spring-harvested hemp, indicating a low risk of corrosion during combustion of hemp biomass (van Loo & Koppejan, 2008). This is different from other straw fuels and agricultural biomass residues, which usually have S/Cl ratios below 2 (*Figure 26*; **Paper III**) (Miltner *et al.*, 2006). However, boilers can be designed for fuels known to have high alkaline and chlorine contents, e.g. cereal straw fuels (Miltner *et al.*, 2006).

Hemp ash properties are superior to those of other straw fuels. Spring-harvested hemp had a Miles index below 0.34 kg/GJ, indicating a low risk of slagging and fouling (Miles *et al.*, 1995). The Miles index and the S/Cl ratio of hemp are similar to those of woody materials and dissimilar to those of straw-like biomass sources such as whole-crop cereals, miscanthus and reed canary grass (*Figure 26*). Straw can potentially have a Miles index below 0.34 kg/GJ and an S/Cl ratio above 2, but the literature also reports ranges for these two indices that indicate a high risk of corrosion during combustion (*Figure 26*). The IDT of hemp is similar to that of wood bark and reed canary grass and higher than that of willow, cereal straw, cereals and miscanthus (*Figure 26*), indicating a low risk for slagging and fouling.

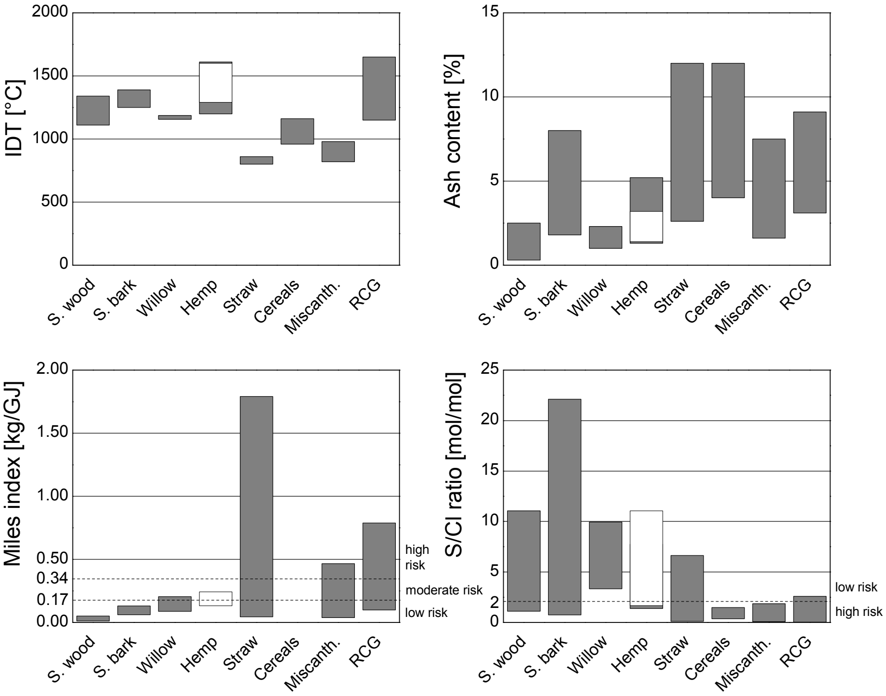

Figure 26. Comparison of initial deformation temperature (IDT), ash content, Miles index and S/Cl ratio for hemp in the present study (white columns) with literature data for selected biomass sources (grey columns), representing solid biofuels from both forestry and agricultural origin. S. = spruce. Cereals = whole-crop cereals. RCG = reed canary grass. Columns denote minimum to maximum values. Bark is mostly combusted in the pulp and paper producing industry and is not likely to be available to biomass boilers combusting energy crops, but given here for reference. References: (BIOS Bioenergiesysteme, 2011; ECN, 2009; Dahl & Brøchner Andersen, 2008; Gilbe et al., 2008; van Loo & Koppejan, 2008; Finell et al., 2006; Forsberg et al., 2006; Norberg, 2006; Obernberger et al., 2006; Kaltschmitt et al., 2000; Wilén et al., 1996; Miles et al., 1995).

Hemp as a solid biofuel has ash characteristics of wood fuels. This is clearly shown in the ternary CaO-SiO_2-K_2O diagram (*Figure 16*; **Paper III**), where spring-harvested hemp samples clustered together with wood fuels such as willow, coniferous wood and wood residues (branches, tops, bark and sawdust). The location of this cluster in the diagram indicates a low risk of significant sintering problems and a high IDT (*Figure 16*) (Fernandez Llorente & Carrasco García, 2005). In contrast, miscanthus, reed canary grass and cereal straw samples clustered together in an area characterised by low IDT and a high risk for significant sintering problems. The boundaries marking the risk zone for sintering were derived from analysis of a selected number of solid biofuels (Fernandez Llorente & Carrasco García, 2005) and therefore act only as an indication of the fuel quality of hemp.

A major competitor to hemp, cereal straw often causes problems with corrosion and sintering (Marmolin *et al.*, 2008; Miles *et al.*, 1995), although these effects can be decreased by washing the straw (Nikolaisen *et al.*, 1998). This procedure requires energy equivalent to about 10% of the energy content of the straw (Nikolaisen *et al.*, 1998). Instead, weathering of cereal straw in the field might be a more practical solution. However, no difference in operating costs was observed in a boiler between use of yellow and grey (weathered) straw (Hinge, 2009). Straw is the more cost-efficient solid biofuel, but due to low DM yield per hectare, availability might be limited within a given transport distance to the CHP plant. In contrast, hemp has approximately twice as high DM yield per hectare (**Paper I**).

Hemp is also dissimilar to miscanthus and reed canary grass, which are more associated with cereal straw as regards the major elements responsible for slagging, fouling and corrosion (**Paper III**). Biomass of miscanthus and reed canary grass is characterised by a much higher ash content and often lower IDT (*Figure 26*) and potentially much greater nutrient removal rates (compare section 4.5.1). However, miscanthus has been shown in this study to have energy yields substantially higher than hemp, while reed canary grass has about the same energy yield per hectare (**Paper IV**). Miscanthus, reed canary grass and willow are cultivated as perennial crops, binding farmers to a specific crop for 10-20 years. This might prove unattractive to farmers, limiting the availability of these crops to a CHP plant.

The high IDT of hemp found in this study indicates that hemp combusted at the normal furnace temperatures of biomass boilers (800-900°C; Baxter *et al.*, 1998) is not likely to cause slagging and fouling. Earlier studies reported that determination of the IDT of fuel samples by observation showed differences between wood and agricultural residues, but did not clearly identify fuel problems (Miles *et al.*, 1995). Furthermore, it has to be noted that the importance of these ash melting properties strongly depends on the type of combustion unit and heat exchanger used (Paulrud, 2004). Most deposits occur during post-combustion and therefore cannot be predicted solely by analysis of the fuel composition (Miles *et al.*, 1995).

Even if the ash fusion test used in the present study (ANSI, 1968) showed high IDT for hemp ash, actual ash melting might start at lower temperatures in combustion tests, e.g. in a production-scale boiler (Paulrud & Nilsson, 2001). For example, IDT values determined by the bed agglomeration test are reported to be 150-200°C and 600°C lower than those by the ash fusion test for reed canary grass with low and high ash content, respectively (Paulrud, 2004). If results are transferable, the bed agglomeration test would probably still give a high IDT for spring-harvested hemp. In addition, the composition of ash produced under laboratory conditions does not always resemble that of ash produced in boiler combustion (Paulrud, 2004).

In order to check the technical suitability of hemp as a solid biofuel, detailed combustion tests with boilers suitable for combustion of straw and wood fuels, respectively, are necessary. Only a few small-scale combustion tests of hemp biomass have been documented (Söderström & Sjölander, 2011; Gilbe *et al.*, 2008; Tung *et al.*, 2008; Sundberg & Westlin, 2005; Jensen & Nikolaisen, 2001; Kaufmann, 1997). Technical problems in handling the fuel or limited fuel availability have resulted in limited data on the combustion quality in some of these combustion tests (Söderström & Sjölander, 2011; Sundberg & Westlin, 2005). Combustion tests are necessary to reveal if actual slagging, fouling and corrosion occurs with hemp as a solid biofuel.

4.4.2 Handling and combustion technology

Hemp as a solid biofuel has a number of viable handling and combustion technology options. Herbaceous fuels, such as straw, miscanthus, reed canary grass and industrial hemp, which are chopped to particulate fuels, have particle shapes and sizes which give them poor bulk handling characteristics, i.e. a low bulk density, poor flow properties and a high tendency to bridge over openings (Mattsson, 1997). Instead of such fuels being handled in bulk, they are often aggregated to bales or compacted to briquettes or pellets before further handling, transport and combustion.

Fuel processing of hemp is likely to require baling of the biomass, since this is a proven, cost-effective system and because the bales function as plugs in the burner openings in some of the newer boilers built for operation on solely straw-like fuels (Hinge, 2009; Sander & Skøtt, 2007). However, to some extent, biomass fuels (e.g. straw, wood) are processed into pellets to facilitate transport (Sander & Skøtt, 2007) and to make them available for boilers with pellet handling systems. Production of hemp bales (Svensson *et al.*, 2010; **Paper IV**), pellets (Nilsson *et al.*, 2011b) and briquettes (Alaru *et al.*, 2011; El Saeidy, 2004) is possible, but may require MC between 10% and 20% (O'Dogherty & Wheeler, 1984).

Use of hemp as a solid biofuel is feasible in several boiler systems. Firstly, hemp can be combusted in boilers built for woody biomass. These boilers are often based on fluidised bed technology, which is normally not suitable for straw due to the low IDT of straw (Hinge, 2009). Although suitable, hemp will probably not be combusted as sole fuel in such boilers, since these are often designed for a MC higher than that of spring-harvested hemp (Sundberg & Westlin, 2005). However, blends of hemp biomass with e.g. fresh wood chips have been successfully combusted in a wood chip boiler (Söderström & Sjölander, 2011). Secondly, hemp can be combusted in boilers built for firing of straw-like solid biofuels, e.g. boilers with moving or vibrating grates (Hinge, 2009). The high flexibility of hemp applications as a solid biofuel may be attractive to both farmers and potential fuel customers.

4.4.3 Variations in hemp fuel properties

Spring harvested hemp has above-average fuel properties that are – in major aspects – independent of location and cultivar. Major fuel properties of hemp were not significantly influenced by different hemp cultivars, trial locations and trial years. The content of the major ash-forming elements, HHV, IDT, S/Cl ratio, Miles index and total ash content of hemp biomass did not vary, although southern and northern field trials were 900 km apart. This indicates that the major fuel properties are stable across a wide range of cultivation parameters and for a number of different cultivars.

Since the soil type can influence content and composition of ash in crops, e.g. reed canary grass (Burvall, 1997), these results have to be confirmed for other soil types and locations.

4.5 Sustainability of hemp biomass production

4.5.1 Nutrient removal and recycling

Plant nutrients in crop cultivation are often supplied in the form of mineral fertiliser. The most important plant nutrients are nitrogen (N), phosphorus (P) and potassium (K). While production of N requires large amounts of energy, P resources are globally limited[39]. To avoid or postpone future depletion and in order to decrease fertiliser-related energy costs, plant nutrients removed from the field by harvest and removal of biomass can partly be recycled in the form of e.g. undegraded biomass (e.g. in digestate) or ash (e.g. from combustion of biomass). The amount of nutrients removed per hectare and the fate of the removed nutrients depends on the application of the biomass.

The digestate can be used as biofertiliser in food, feed and energy crop cultivation. This nutrient recycling via digestate results in approx. 30% less energy input in cultivation of autumn-harvested hemp compared with spring-harvested (**Paper IV**). Amounts of nutrients removed from the field are high for biomass used for biogas production (*Figure 27*). In the anaerobic digestion process, biomass is partly degraded and mineralised. When the digestate containing undigested biomass is spread on fields for use as biofertiliser, mineralised nitrogen is available to plants. However, during storage and spreading mineralised nitrogen may be partly lost to the atmosphere. P and K can be assumed to be returned to the field almost entirely in the digestate. Even if not all nutrients are mineralised (plant-available), continuing mineralisation of the undigested biomass will replenish soil nutrient stocks for P and K. Similarly, biomass-bound nitrogen is released and plant-available at a later time. Digestate can therefore be considered to be both directly fertilising (similarly to mineral fertiliser) and a long-term biofertiliser. This can be of advantage if plants fertilised with digestate can take up the nitrogen later in the growing season when it is mineralised. This is best ensured by plants such as sugar beet, maize or hemp that are harvested late in the autumn. If nitrogen is not taken up and bound organically at the time of mineralisation, further amounts of nitrogen may be lost to the atmosphere or – worse - to water bodies causing eutrophication.

The amounts of nutrients removed from the field are low for hemp solid biofuel production (*Figure 27*). The decreases in the content of the nutrients is probably related to both nutrient losses from the plants (e.g. senescing leaves) and wash-out effects by precipitation (Nikolaisen *et al.*, 1998; Landström *et al.*, 1996). Ash from large-scale combustion of the biomass can potentially be used as a fertiliser. However, combustion may also concentrate undesirable elements (e.g. heavy metals) in the ash. Nutrient recycling in the form of ash to agricultural fields is normally only practised if the ash is from a defined source,

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[39] Besides being limited, P-rich ores often also contain amounts of heavy metals, e.g. cadmium (Cd). Purification of P from ores with relatively high Cd content is significantly more costly than that of Cd-poor ores.

e.g. cereal straw (Ottosson *et al.*, 2009) and energy crops, but usually not from combustion of other materials.

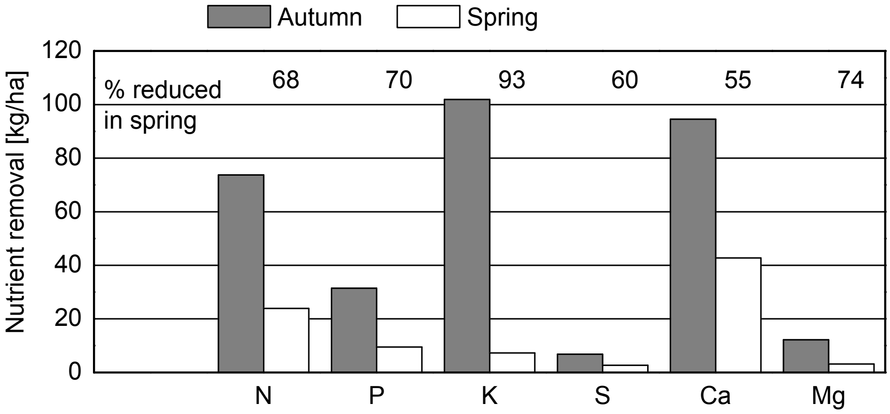

Figure 27. Average removal of selected macro-nutrients at harvest in autumn (grey columns) and in spring (white columns) corresponding to the amount of biomass harvested per hectare.

Plant nutrients in other sources, e.g. waste water, can be utilised by fertilising crops (Li *et al.*, 2009). Since these waste streams often contain undetermined amounts of organic substance that are potentially harmful to humans and animals (Palmquist & Hanæus, 2005), fertilisation of crops for feed and food production is not appropriate. Fertilisation of energy crops with these urban nutrients is advantageous in several ways. Firstly, energy for production of the mineral fertilisers replaced by urban nutrients is saved. Secondly, waste water treatment costs are reduced significantly (Rosenqvist & Ness, 2004). Thirdly, renewable energy can be produced from the energy crops. Trials with willow acting as vegetation filter for waste water have been successful (Hasselgren, 1999; Perttu, 1999). However, issues concerning risks of accumulation of heavy metals and recalcitrant organic constituents in the cultivated soil and potential leaching of plant nutrients are not yet sufficiently investigated (Perttu, 1999).

Hemp biomass had a low content of cadmium in this study (**Paper III**), but on contaminated soils, hemp is able to extract heavy metals from the soil in amounts higher than many other agricultural crops (Angelova *et al.*, 2004). Thus heavy metals could be concentrated in the plant biomass. During combustion in large-scale combustion plants, ash fractions with high heavy metal content could be removed from the recycling scheme for plant nutrients (Ottosson *et al.*, 2009; Obernberger *et al.*, 1997). Thereby, the amount of heavy metals in the cycle would not increase, but rather decrease, while the major fraction of plant nutrients, except nitrogen[40], could be recycled e.g. to agriculture.

4.5.2 Pesticide use

Hemp cultivation requires very limited amounts of pesticide (see section 1.6.3). Few insect pests are known to exist in hemp crops and fungal diseases are rare (McPartland & Hillig, 2006; Ranalli, 1999). Since hemp plants shade the ground quickly after sowing and thereby outgrow weeds, herbicides are not required (van der Werf *et al.*, 1995; Lotz *et al.*, 1991). However, a weed free seedbed is required. This can be achieved for example by preparing a stale seedbed in combination with a harrowing step prior or in combination with drilling (Melander *et al.*, 2005).

Pesticide requirements have a potentially strong influence on the energy input in cultivation, since energy requirements for pesticide production are high (Kaltschmitt & Reinhardt, 1997; Pimentel, 1980). Many other annual energy crops in large-scale cultivation require relatively large amounts of pesticides, e.g. maize and sugar beet cultivated for biogas production (Meissle *et al.*, 2010; Märländer *et al.*, 2003). However, in large monocultures of hemp, pests (e.g. the hemp flea) could potentially become an issue as well (Bocsa & Karus, 1998). In well-designed crop rotations, a low pesticide use in hemp cultivation can be expected even for large-scale cultivation.

4.5.3 Crop rotation effects

Hemp is a strong weed suppressor, resulting in low herbicide requirements for hemp cultivation. Furthermore, in a crop rotation this weed suppression effect can even improve the weed situation for the following crop (van der Werf *et al.*, 1995).

Similarly, hemp suppresses soil pathogens and soil health might therefore be improved with introduction of hemp into a given crop rotation. (Kok *et al.*, 1994). Hemp has been reported to be an excellent preceding crop for cultivation of cereals crops (Deeley, 2002), resulting in yield increases of 10-20% in cereals (Bocsa & Karus, 1998). For winter cereals this is only possible if hemp is harvested in autumn, e.g. as biogas substrate or for fibre production. For spring-harvested hemp used as solid biofuel, practically any spring-sown crop can be used in succession.

Hemp, being an annual crop, is relatively easy to insert into an existing crop rotation. There it may function as a break crop[41], e.g. in cereal cultivation.

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[40] Nitrogen is lost to the atmosphere during combustion.

Farmers interested in cultivating energy crops are often hesitant about tying fields into the production of one crop, e.g. willow and miscanthus, over the economic lifespan of the plantation, i.e. 10-20 years (Deeley, 2002).

Cultivation of hemp over two to three years in the same field does not lead to significant biomass yield losses, due to a high self-tolerance of hemp (Bocsa & Karus, 1998). Therefore, hemp functions very well as a crop in crop rotations.

4.5.4 Economics

Hemp biomass production for energy purposes is economically feasible even for small-scale cultivation areas. However, non-energy applications may require cultivation on a much larger scale. For example, there is interest in using hemp for production of fibre boards. However, implementing hemp as a raw material source for this purpose in just one production line would require a volume of biomass corresponding to cultivation on approx. 1.000 hectares (Svennerstedt *et al.*, 2011). Today, implementation of such a large-scale cultivation of hemp from one year to another would be difficult, since practical experience is lacking among farmers and advisors. In contrast, options for using hemp biomass for energy purposes, e.g. briquette production from small-scale hemp cultivation (10-20 ha), can already be commercially viable (Jonsson, 2011; Forsberg *et al.*, 2006). Based on such small-scale start-ups, experience and knowledge can be built to implement use of industrial hemp on a larger scale for both energy and non-energy purposes. Therefore, use of hemp for energy purposes might prove to be a stepping stone in building industry structures that can use hemp for non-energy purposes.

In a biorefinery, combination of several production pathways, e.g. for both energy and non-energy products, may improve energy efficiency and overall economics. This concept integrates production of a selection of high-value products (e.g. building block chemicals, fibres) and subsequent use of low-value bulk residues, e.g. for production of renewable energy carriers. Industrial hemp, with its high biomass yield (**Paper I**), high fibre content (van der Werf, 1994), oil-rich seeds with an interesting profile of polyunsaturated fatty acids (Vogl *et al.*, 2004; Grigoriev, 2002) and antioxidants (Blade *et al.*, 2006) and promising fermentation conversion efficiency (**Paper II**), is an interesting biomass source in this respect.

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41. The break crop ’breaks’ the series of crops belonging to the same botanical family in order to deprive soil-borne crop pathogens of their host and thereby decreasing the magnitude of infection for the subsequent crop (Kirkegaard *et al.*, 1997).

4.5.5 Environmental impact of hemp cultivation

Hemp biomass cultivation and use has a relatively low overall environmental impact. The environmental impact of a crop cultivated for energy use can be measured, e.g. as the sum of all emissions caused during the cultivation, harvest, transport and storage. Similarly to the methodology applied for compilation of an energy balance, major field operations and production means can be labelled with corresponding emissions. Besides emissions of greenhouse gases, other impact categories[42] need to be accounted for.

Hemp has been reported to have high biodiversity friendliness when grown as a fibre and food crop (Montford & Small, 1999). Furthermore, hemp has been characterised as a low-input and low-impact crop[43] relative to food crops, e.g. sugar beet and potato (van der Werf, 2004). For biogas-based electricity production, hemp had a disadvantageous greenhouse gas balance due to an unfavourable energy balance (Plöchl *et al.*, 2009). In principle, **Paper IV** has confirmed the unfavourable energy balance for all energy crops used for electricity production from biogas, especially if heat from power generation is not utilised. Biodiesel production from hemp seed oil has been reported to have a much lower overall environmental impact than fossil diesel, even in case where the stalks and leaves were not used for energy purposes (Casas & Rieradevall i Pons, 2005). However, no studies to date have investigated the more energy-efficient production pathways of biogas for vehicles and CHP from hemp for their environmental impact.

Evaluation of the environmental impact of hemp cultivation lay outside the scope of this thesis. However, an analysis of hemp crop cultivation of the type included in a life cycle assessment (LCA) is required for further evaluations of hemp as an energy crop, e.g. against sustainability criteria for biofuels (EC, 2009). Furthermore, an LCA study of the different energy and non-energy application pathways of hemp is required as a basis for comparison of different energy carriers and non-energy products of hemp.

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[42] Impact categories include global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical smog, terrestrial toxicity, human health, resource depletion, land and water use (NRML, 2006).

[43] All inputs in crop cultivation and biomass use result in emissions that can cause an environmental impact, e.g. carbon dioxide emissions causing global warming.

5 General conclusions

Industrial hemp has a high energy yield per hectare for both solid biofuel and biogas production that is similar or superior to that of most energy crops common in northern Europe (**Papers I** and **IV**).

The high energy yield of biogas from industrial hemp is based on a high biomass yield per hectare and a good specific methane yield with large potential for increases by pretreatment of the biomass. Harvest date in autumn has no significant impact on the specific methane yield and therefore the methane energy yield per hectare is highest in autumn when the hemp biomass yield is highest. Hemp as a biogas substrate surpasses crops used for first generation biofuel production (e.g. wheat, rapeseed) and with pretreatment might even compete with maize and sugar beet for biogas production. Industrial hemp is a high-yielding crop for biofuel production based on lignocellulosic crops (**Papers II** and **IV**)

The energy yield per hectare of industrial hemp for use as a solid biofuel is highest in autumn when the biomass yield is highest. However, important combustion-related fuel properties, such as content of alkali metals and chlorine, ash melting temperature and ash content, are significantly improved when industrial hemp is harvested in spring instead of in autumn. The major fuel properties of hemp are not influenced by choice of cultivar and large differences in latitude between cultivation sites. Fuel properties of hemp are similar to those of wood and willow and superior to those of straw, miscanthus and reed canary grass. Despite lower energy yield per hectare when spring-harvested, hemp competes well with that of products from forestry (e.g. wood chips) and agriculture e.g. straw, miscanthus, reed canary grass, willow) for heat, power and combined heat and power (CHP) production (**Papers I** and **IV**).

Industrial hemp has a good net energy yield per hectare in most applications, except electricity production from biogas. This option shows unfavourable net energy yields for any energy crop, especially if the heat from power generation is not utilised. Furthermore, hemp has good energy output-to-input ratios and is therefore an above-average energy crop. Use of hemp as solid biofuel has the highest net energy yield per hectare and energy output-to-input ratio. Use of hemp as a biogas substrate suffers from higher energy inputs and lower conversion efficiencies, but produces a high quality vehicle fuel (**Paper IV**).

Advantages over other energy crops are also found outside the energy balance, e.g. low pesticide requirements, good weed competition and suitability for crop rotations. Future improvements in hemp biomass and energy yields may strengthen its competitive position against maize and sugar beet for biogas production and against perennial energy crops for solid biofuel production.

6 Areas of future research

In order to implement hemp as an energy crop in large-scale bioenergy carrier production, further analyses of its sustainability are required. Environmental, economical and social impacts have to be studied further in order to create a sound knowledge basis for comparisons with competing energy crops and other biomass types.

The energy balances complied in this thesis can be used to apply environmental, economic and social costs and benefits to the different applications of industrial hemp biomass. Specifically, greenhouse gas emissions and biomass production costs of hemp as biogas substrate and solid biofuel are of major interest.

Biomass yield may be increased by a detailed nutrient balance for industrial hemp accounting for plant and soil nutrient contents, as well as corresponding water requirements.

The good combustion properties of spring-harvested hemp biomass as indicated by the fuel property analyses in this study need to be confirmed in large-scale combustion tests. Furthermore, more field trials, both in other locations and on other soil types, are needed to confirm the independence of the above-average fuel properties of spring-harvested hemp from choice of cultivar, location and soil type.

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Svensk sammanfattning

Industrihampa (*Cannabis sativa* L.) – en högavkastande energigröda

Bioenergi är för närvarande den snabbast växande källan för förnybar energi. Strängare hållbarhetskriterier för produktion av fordonsbränslen och ett ökat intresse för kraftvärmeproduktion baserad på biomassa har skapat efterfrågan på högavkastande energigrödor med god omvandlingseffektivitet.

Denna avhandling presenterar studier av industrihampa som energigröda för produktion av biogas och fastbränsle. I fältförsök har utvecklingen av biomassa- och energiavkastning, specifikt metanutbyte och biomassans bränsleegenskaper undersökts under tillväxten och den efterföljande vissningsfasens förlopp, dvs. från höst till följande vår.

Hampans energiavkastning för både biogas- och fastbränsleproduktion är lika hög som eller överlägsen de flesta andra vanliga energigrödor i Nordeuropa. Den höga energiavkastningen för hampa i form av biogas beror på en kombination av hög biomassaavkastning och högt specifikt metanutbyte. Det finns dessutom en stor potential att höja det specifika metanutbytet med hjälp av olika förbehandlingsmetoder, t.ex. ångexplosion. Energiavkastningen per hektar i form av metan är högst om hampan skördas under hösten, dvs. när biomassaavkastningen är högst.

Energiavkastningen för hampa som fastbränsle är också högst under hösten. Denna skördetidpunkt är dock ogynnsam för viktiga bränsleegenskaper, t ex halt av alkalimetaller, klor och aska samt asksmälttemperatur. Om hampan får stå kvar på fältet över vintern och skördas först under våren, så förbättras dessa bränsleegenskaper betydligt. De viktigaste bränsleegenskaper påverkas däremot inte av årsmån, stora skillnader i latitud eller val av hampasort.

Nettoenergiavkastningen per hektar för hampa är bra för användning som biogassubstrat eller fastbränsle. Dessutom har hampa relativ hög energikvot mellan utbyte och insats (output/input-förhållande). Hampa kan därför anses vara en energigröda som är bättre än genomsnittet.

En jämförelse av olika energisystem baserade på hampa visade att användning av hampa som fastbränsle gav högst nettoenergiavkastning och energikvot (output/input). System baserade på hampa för produktion av biogas krävde högre energiinsatser och gav lägre omvandlingseffektivitet, men gav å andra sidan fordonsbränsle, dvs. en energibärare av högre kvalitet.

Utöver gynnsam energibalans har hampa andra fördelar, t.ex. lågt pesticidbehov bl.a. genom en mycket god förmåga att konkurrera med ogräs. Hampa är en lämplig avbrottsgröda i spannmålsintensiva växtföljder. Den stora potentialen att öka hampans biomassa- och energiavkastning kan i framtiden stärka dess konkurrenskraft mot majs och sockerbetor för biogasproduktion och mot perenna grödor för produktion av fastbränsle.

Deutsche Zusammenfassung

Industriehanf (*Cannabis sativa* L.) – eine ertragreiche Energiepflanze

Bioenergie ist die zurzeit am schnellsten wachsende Quelle, die zur Produktion erneuerbarer Energien beiträgt. Strengere Nachhaltigkeitskriterien für die Produktion von Treibstoffen und ein wachsendes Interesse an Kraftwärmekopplung (KWK) aus Biomasse haben zu einer erhöhten Nachfrage an ertragreichen und effizient zu Energieträgern umwandelbaren Energiepflanzen geführt.

In der vorliegenden Studie wurde die Eignung von Industriehanf als Energiepflanze zur Produktion von Biogas bzw. Festbrennstoff untersucht. In Feldversuchen wurden Biomasse- und Energieerträge über den Zeitraum von Wachstum und den nachfolgenden Verwelkungsprozess (d.h. vom Herbst bis zum folgenden Frühjahr) untersucht und in Zusammenhang mit dem spezifischen Methanertrag bzw. der Zusammensetzung der Biomasse gestellt.

Die Energieerträge von Hanf zur Verwendung als Biogassubstrat bzw. als Festbrennstoff erwiesen sich als ähnlich hoch oder höher im Vergleich zu den Erträgen der meisten in Nordeuropa üblichen Energiepflanzen. Der hohe Biogas-energieertrag von Hanf beruht auf der sehr hohen Biomasseproduktion per Hektar und einem guten spezifischen Methanertrag. Es besteht außerdem ein großes Potenzial zur Steigerung des Methanertrages mit Hilfe geeigneter Vorbehandlungsmethoden. Soll Hanf als Biogassubstrat verwendet werden, ist Ernte im Herbst zum Zeitpunkt der höchsten Biomasseerträge vorteilhaft.

Der höchste Energieertrag von Hanf als Festbrennstoff wird ebenfalls im Herbst erreicht. Zu diesem Zeitpunkt sind jedoch wichtige verbrennungsrelevante Stoffeigenschaften wie zum Beispiel der Gehalt an Alkalimetallen, Chlor und Asche als auch die Ascheschmelztemperatur unvorteilhaft. Wird der Hanf über den Winter im Feld belassen und erst im Frühjahr geerntet, verbessern sich diese Brennstoffeigenschaften deutlich. Die wichtigsten

Brennstoffeigenschaften von Hanf sind unabhängig von Variationen der Wachstumsbedingungen, Breitengrad und Cultivar.

Hanf erzielt gute Nettoenergieerträge per Hektar in den meisten Anwendungen. Weiterhin ist das Verhältnis von erzielter zu eingesetzter Energiemenge (Output/Input-Verhältnis) vergleichsweise hoch in den meisten untersuchten Anwendungen. Hanf ist daher eine überdurchschnittliche Energiepflanze. Als Festbrennstoff hat Hanf die höchsten Nettoenergieerträge und Output/Input-Verhältnisse. Als Biogassubstrat leidet Hanf unter höheren Energieeinsätzen und niedrigerer Umwandlungseffizienz, liefert jedoch Fahrzeugtreibstoff, einen sehr hochwertigen Energieträger.

Über eine günstige Energiebilanz hinaus hat Hanf andere Vorteile, zum Beispiel einen niedrigen Pestizidbedarf, gute Unkrautbekämpfungseigenschaften und gute Vorfruchtseigenschaften (als *break crop*) in Getreide-intensiven Fruchtwechseln. Das große Potenzial für zukünftige Steigerungen der Biomasse- und Energieerträge von Hanf kann dessen Konkurrenzfähigkeit gegenüber Mais und Zuckerrüben zur Produktion von Biogas und gegenüber mehrjährigen Pflanzen zur Produktion von Festbrennstoff weiter verstärken.

Appendix

Table A1. *Hemp varieties, their utilisation, relevant plant parameters and data on approval within the EU and Canada.*

Cultivar	Utilisation	Sex	Bred in	Maturity group	Year of breeding	EU 2009	EU 2010	EU 2011	Canada 2011
52092		dioecious	Turkey						
52137		dioecious	Turkey						
Alp King	fibre	dioecious	Switzerland	medium					
Alyssa[a]	seed/fibre		Canada		2004				x
Anka	seed	monoecious	Canada		1999				x
Armanca			Romania					x	
Asso	fibre	dioecious	Italy		2004	x	x	x	
Beniko	fibre	monoecious	Poland	early	1985	x	x	x	
Bialobrzeskie	fibre	monoecious	Poland	medium early	1968	x	x	x	
Canda			Canada						x
Cannakomp			Hungary		2003	x	x	x	
CanMa			Canada						x
Carma	fibre	monoecious	Italy			x	x	x	
Carmagnola	fibre	dioecious	Italy	late	landrace	x	x	x	x
CS[b]	fibre		Italy		1960s	x	x	x	
Carmen	seed/fibre		Canada						x
Carmono	fibre	monoecious	Italy		1990s				
CFX-1			Canada						x
CFX-2			Canada						x
Chamaeleon	fibre	dioecious	Netherlands		2002	x	x	x	
Codimoni[c]	fibre	monoecious	Italy		2004	x	x	x	
Crag	fibre		Canada						x
CRS-1			Canada						x
Delores	seed		Canada		2007				x
Delta Llosa	fibre		Spain			x	x	x	
Delta 405	fibre		Spain			x	x	x	
Denise	fibre, seed	monoecious	Romania			x	x	x	
Deni[d]			Canada						x
Diana	fibre, seed	monoecious	Romania				x	x	
Dioica 88	fibre	dioecious	France	very late	1998	x	x	x	
Dneprovskaya Odnodomnaya		monoecious	Ukraine		1980				
Dolnoslaskie			Poland						

Cultivar	Utilisation	Sex	Bred in	Maturity group	Year of breeding	EU 2009	EU 2010	EU 2011	Canada 2011
Eletta Campana	fibre	dioecious	Italy		1960s				
Epsilon 68	fibre	monoecious	France	late	1996	x	x	x	
Ermes	fibre	monoecious	Italy		1990s				
Ermakovskaya Mestnaya			Russia		landrace				
ESTA-1	seed		Canada						x
Fasamo	fibre	monoecious	Germany	very early	1998		x	x	x
Fédora 17	fibre	monoecious	France	medium	1998	x	x	x	
Fédora 19	fibre	hybrid population	France	early					
Fédrina 74	fibre	hybrid population	France	medium-late			x	x	x
Félina 32	fibre	monoecious	France	early	1998	x	x	x	
Félina 34	fibre	hybrid population	France	medium-early	1974	x	x		x
Férimon 12	fibre	monoecious	France	early	1981	x	x	x	x
Ferrara		dioecious	Italy		landrace				
Fibramulta 151	seed, fibre	dioecious	Romania	medium	1965				
Fibranova	fibre	dioecious	Italy	late	1950s	x	x	x	x
Fibriko			Hungary		1989				x
Fibriko TC			Hungary		2007				
Fibrimon	fibre	monoecious	Germany		1950s				
Fibrimon 21	fibre	monoecious	France		1950s				
Fibrimon 24	fibre	monoecious	France		1972	x			x
Fibrimon 56	fibre	monoecious	France	medium	1972				x
Fibrimor	fibre	dioecious	Italy		2003	x	x	x	
Fibrol			Hungary			x	x	x	
Finola	seed	dioecious	Finland	early	2003				x
Flajsmanova			former Yugoslavia						
Futura 75	fibre	monoecious	France	medium-late	1998	x	x	x	
Futura 77	fibre	monoecious	France	medium-late			x	x	
FxT	fibre, seed	monoecious	Hungary	medium-early					
Glera		monoecious	Ukraine						
Gluchivski-33		monoecious	Ukraine						
Gluchivski-46		monoecious	Ukraine						
Glukhov 33			Ukraine						
Grace			UK		2004				
Hei Bei	fibre								
Helvetica 01		dioecious	Switzerland	medium-early					
Helvetica 02		dioecious	Switzerland	medium-early					
Helvetica 03		dioecious	Switzerland	medium					
Helvetica Tell		dioecious	Switzerland	medium-early					
Ida			Canada						
Irene	fibre, seed	monoecious	Romania	medium-early	1995				
Joey			Canada						x
Jutta			Canada						x
K (Chinese) x V (wild)	fibre		Hungary						
KC Dóra			Hungary		2009		x	x	
Kenevir	fibre	dioecious	Turkey						
Kinai Egylaki		monoecious	China						

Cultivar	Utilisation	Sex	Bred in	Maturity group	Year of breeding	EU 2009	EU 2010	EU 2011	Canada 2011
Kinai Kétlaki	fibre	dioecious	China						
Kinai unisexualis	fibre	dioecious, but only females	Hungary						
Kompolti	fibre	dioecious	Hungary	late	1954	x	x	x	x
Kompolti Hybrid TC	fibre, seed	dioecious	Hungary	late	1983	x	x	x	
Kompolti Hyper Elite			Hungary						
Kompolti Sargaszaru			Hungary		1974				x
Kozuhara zairai	fibre	landrace	Japan						
Krasnodarskaya	fibre		Former USSR						
Kuban		dioecious	Ukraine		1984				
Lipko		hybrid population	Hungary		2003	x	x	x	
Livoniae	seed	dioecious	Latvia	medium					
Lovrin 110	fibre, seed	dioecious	Romania	medium-late	1981	x	x	x	x
Mechaja copt			Bulgaria						
Medisins					1998				
Moldovan	seed, (fibre)	dioecious	Romania	medium					
Mona			Sweden						
Moniseed			Hungary		2004	x		x	
Monoica			Hungary			x	x	x	
Multiseed			Hungary		2004	x		x	
Novosadska[e]	fibre	dioecious	former Yugoslavia	late					
Novosadska konplja			former Yugoslavia		1950s				
Novosadska plus		dioecious	former Yugoslavia	late					
Odnodomnaja Bernburga	fibre		former USSR						
Pesnica			Slovenia		landrace				
Petera	fibre		Canada		2007				x
Rano		dioecious	Germany						
Rastslaviska	fibre		Czech Republic						
Red petiole	fibre	dioecious	Italy		2002	x	x	x	
Rudnik			Slovenia						
S-204	fibre	monoecious	France						
S-206	fibre	monoecious	France						
Santhica 23	fibre	monoecious	France	medium	1996	x	x	x	
Santhica 27	fibre	monoecious	France	medium	2003	x	x	x	
Santhica 70	fibre	monoecious	France	late	2007	x	x	x	
Schurig			Germany						
Secuieni 1	fibre, seed	monoecious	Romania	medium-early	1984				
Silesia	fibre	monoecious	Poland?			x	x	x	
Silistrensi			Bulgaria						
Silvana			Romania			x	x	x	
Solotonosker 11[f]		monoecious	Ukraine	medium-early					x
Solotonosker 15[f]			Ukraine	medium-early					x
Suprafibra	fibre		Italy		1960s				
Swissmix		dioecious	Switzerland	early					
Szarvasi			Hungary			x	x	x	
Szegedi 9	fibre		Hungary						
Tibolaj	fibre								
Tiborszallasi	fibre	dioecious	Hungary	medium-	2003				

Cultivar	Utilisation	Sex	Bred in	Maturity group	Year of breeding	EU 2009	EU 2010	EU 2011	Canada 2011
				late					
Tisza			Hungary					x	
Tygra	fibre	monoecious	Poland			x	x	x	
UC-RGM			Canada						x
Uniko B	fibre	dioecious	Hungary	medium	1969	x	x	x	x
Uniko-B (F1)	fibre	unisexual	Hungary	medium					
USO 1[f]	fibre		Former USSR						
USO 11[f,g]	fibre	monoecious	Ukraine	medium-early	1984				x
USO 13[f]		monoecious	Ukraine		1986				
USO 14[f]	fibre, seed	monoecious	Ukraine	very early-early	1999				x
USO 15[f,g]		monoecious	Ukraine		1995				x
USO 16[f]	fibre		Ukraine		1980				
USO 31[f]	fibre, seed	monoecious	Ukraine	very early-early	1997	x	x	x	x
V (wild) x Kompolti	fibre		Hungary						
Waliser Queen		dioecious	Switzerland	very early					
Wielkopolskie			Poland				x	x	
X59			Canada						x
Yvonne			Canada						x
Zenica		dioecious	Ukraine		1990				
Zenit	seed, fibre	monoecious	Romania				x	x	

[a] also known as *Alisa*
[b] also known as *Carmagnola Selezionata*
[c] also knwon as *Codimono*
[d] also known as *Denny*
[e] also known as *Novosadski*
[f] also known as *Juznaja Odnovremenno Sozrevajuscaja* or *JSO* or *Juso* or *Yuso*
[g] also known as *Zolotonosha* or *Solotonosker* or *Zolotosskaja*