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Effect of harvest date on combustion related fuel properties of industrial hemp (*Cannabis sativa* L.)

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HIGHLIGHTS

- Major fuel properties are significantly improved if hemp is harvested in spring.
- Cultivar and location do not influence major fuel properties of hemp.
- Major fuel properties of hemp are similar to those of wood and willow.
- Hemp has major fuel properties superior to straw, miscanthus and reed canary grass.
- Large-scale combustion tests on hemp and blends of hemp are needed.

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ABSTRACT

Energy crops can increase biomass availability for large-scale biomass-fired heat, power and CHP plants, which can contribute greatly to mitigation of greenhouse gas emissions. Industrial fibre hemp (*Cannabis sativa* L.) is a potential high biomass and energy yielding crop intended for use as solid biofuel, but its fuel properties are insufficiently characterised.

Hemp was grown in two independently planned field studies 900 km apart, in southern and northern Sweden. The northern field trials comprised two seasons, two locations and four different cultivars of hemp, while the southern field trial included one hemp variety and one season. Mineral elemental composition (C, H, O, N, S, Cl, Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Na, Ni, P, Pb, Rb, Se, Si, Sn, Sr and Zn), heating value, moisture content and initial ash deformation temperature were determined on samples taken between autumn and spring.

Spring harvesting significantly improved relevant combustion fuel properties such as moisture content, alkali and ash content and heating value in comparison with autumn harvest. Major fuel properties were not influenced by choice of cultivar or geographical location.

Spring-harvested industrial hemp was found to have high initial ash deformation temperatures and a mineral composition similar to that of willow and coniferous wood, indicating that the ash resulting from its combustion will have a low risk of slagging and fouling. Relevant combustion fuel properties were superior to those of other available agricultural biomass feedstocks, such as cereal straw, miscanthus and reed canary grass (straw fuels). Therefore, hemp is a suitable solid biofuel for large-scale CHP plants and small-scale heating boilers as pellets or briquettes. This study characterised hemp as a solid biofuel, but large-scale combustion tests and an economic analysis are needed to determine the competitiveness of hemp compared with other sources of biomass.

1. Introduction

Heat and power production from combustion of biomass can make a major contribution to mitigation of greenhouse gas emissions [1,2]. Large-scale biomass-fired boilers for production of heat, power or combined heat and power (CHP) are currently in production worldwide [3]. Co-firing of biomass with fossil fuels, e.g. coal, was also employed in over 200 plants in 2005, mainly in Europe and North America [4]. Wood products from forestry are generally the main fuel used in such plants [3]. However, a number of power plants now use agricultural residues (e.g. cereal straw) as main fuel [5] and more are in the planning stage (e.g. [6]). The high transport cost of low bulk density herbaceous biomass limits the

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availability for such large-scale plants or calls for densification of the fuel before transport.

In such areas, dedicated energy crops with high biomass and energy yields per hectare could compete economically with the by-product cereal straw [7] and, if managed properly, also with wood fuel [8]. Few energy crops have been reported as potential solid biofuels in cold climate regions, such as Northern Europe. One promising crop is hemp, which has been shown to be competitive compared with forestry wood fuels and agricultural residues in terms of energy yields per hectare [9].

Industrial fibre hemp (*Cannabis sativa* L.) is an annually cultivated and harvested herbaceous crop that has above average biomass and energy yields in Northern Europe [9–11], even though it was developed for fibre purposes [12–14]. Furthermore, hemp can be grown as a break crop in cereal crop rotations, thereby increasing fuel availability without widening the transport radius for a given CHP plant. In Sweden, hemp grown for use as solid biofuel is left on the root for drying in the field during winter and then harvested in early spring when the moisture content (MC) has decreased to levels suitable for direct storage (MC < 30%; [15]). A low MC is important if the economic value (i.e. the fuel price) of the solid biofuel is based on its lower heating value (LHV), as is the case in Sweden and many other countries [16].

The competitiveness of an energy crop as combustion fuel is influenced by multiple factors, e.g. its fuel properties, energy yield per hectare, seasonal availability and its production economics. Fuel properties can be divided into physical and chemical properties. Physical properties, e.g. particle size, bulk density, angle of repose and bridging tendency, can be adjusted by physical treatment, e.g. grinding, milling or compaction.

Chemical fuel properties of a biofuel include e.g. elemental composition, ash content and heating value. The chemical composition of a biofuel affects its heating value, ash content, ash melting behaviour (how and at what temperature the ash melts), and characteristics of flue gas and fly ash (fine ash particles in the flue gas) [17]. The composition and amounts of minerals that form ash during combustion of the biomass determine its melting behaviour, corrosiveness and tendency to agglomerate and sinter. These ash particles can form layers of sintered material on boiler walls and other equipment e.g. heat exchangers, which can lead to lower process efficiencies, corrosion and mechanical damage [18], resulting in higher investment and operational costs. The elements Si, K, Na, Al, Mg, Ca, Cl, S and P have been reported to cause ash-related problems such as slagging, fouling and corrosion [19]. Chemical fuel properties are inherent and hard to change once the crop is harvested [20]. Therefore, it is of key importance to investigate the influence of harvest date on the major fuel properties of a biofuel, i.e. the major ash-forming elements Ca, K, Mg, Al, Fe, Mn and Na as well as heating value, ash deformation behaviour, S/Cl ratio, Miles index and total ash content.

In order to establish hemp as a raw material for large-scale biomass combustion, its fuel properties and technical requirements have to be determined. Few studies have presented data on fuel characteristics of hemp [12,14,21] and in a recent large review of energy crop fuel properties, data for industrial hemp are lacking [22]. To our knowledge, no published study has investigated the development of extended fuel properties of hemp during growth and senescence of the crop, i.e. harvest in autumn, winter and spring.

The aim of this study was therefore to determine the combustion-relevant fuel properties, such as higher and lower heating value, moisture content and content of ash forming elements, as well as content of major plant nutrients in industrial hemp at different harvest dates. Another aim was to investigate the influence of cultivar and geographical location to a limited extent. A final aim was to compare the fuel properties of hemp biomass harvested at a date optimal for use as solid biofuel with those of other solid biofuels.

2. Materials and methods

2.1. Biomass cultivation and sampling

Samples for determination of fuel properties came from two field studies of hemp biomass production that were independently planned and conducted in different climate zones. One of the field studies was located in southern Sweden (Nöbbelöv, outside Lund), the other at two sites in northern Sweden (Röbäcksdalen, Umeå, and Degernäs, outside Umeå, ca 900 km north of the southern site). The sites were characterised by a low soil clay content (<20%) and a humus content of 3–6% (Table 1).

Hemp can grow well under temperate and cool climate conditions [23]. The crop grows best on well-drained, fertile, medium-heavy soils, especially silty loam, clay loam, and silty clays [23].

For determination of MC, three plants per replicate plot were hand-cut close to the ground, leaving 1–3 cm long stubble. Stems with leaves from each sampling site were collected in a sealed tared polyethylene bag. The bags were weighed within 2 h of sampling. For mineral analysis, two sets of three additional plants per replicate plot were collected in the same way as for MC determination. Samples for mineral analysis were air-dried at 20 °C until no further weight loss occurred. After drying, the samples were stored at 20 °C before being sent to accredited commercial laboratories for analysis. All sampling sites had more than 4 m clearance from the plot border, in order to avoid border effects. Sampling occurred at dates specified in Table 1. Note that the southern and northern trials were sampled differently and therefore corresponding sampling dates were termed ‘autumn’, ‘winter’ and ‘spring’ to allow direct comparison. Throughout the text, these terms refer to the sampling dates given in Table 1. References to trial years in the following text refer to the year in which the relevant field trial was established.

2.2. Sample analyses

Methods used for sample analysis are shown in Table 2. The higher heating value (HHV) of the biomass was determined using a bomb calorimeter [24]. Samples for analysis of MC were dried at 105 °C for 24 h and MC was determined from the weight difference of samples before and after drying [25].

The content of C, H, O, N, S and Cl was determined in the first set of biomass samples. Biomass content of C, H and N was analysed in a Leco CHN 1000 elemental analyser by the LECO-1 method using a combustion analyser (Leco, Michigan, USA). Biomass samples were ground to particles smaller than 1 mm [26] and a subsample was incinerated at 1050 °C for detection of elements. Further analyses of prepared samples [26] included determination of Cl content by titration of Eschka mixture [27] and of S content by a high temperature tube furnace combustion method at 1350 °C [28]. The content of O was calculated according to ISO standard 1928 [24]. Total ash content was determined by measuring the weight loss under combustion of the biomass samples at 550 °C [29]. Initial deformation temperature (IDT) of ash was measured in a Leco AF 600 ash fusibility determinator (Leco, USA) by automatically monitoring ash cone deformation at increasing temperature in an oxidising atmosphere [30].

Extended mineral analysis was carried out on the second set of biomass samples. Analysis of samples from southern Sweden included determination of content of plant macronutrients (P, K, Ca and Mg), as well as micronutrients and trace elements (Al, B, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Na, Ni, Pb, Rb, Se, Si, Sn, Sr and