

WILLOW-BASED MIXED FEEDSTOCK FOR PELLET FUEL PRODUCTION

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The aim of this work was to produce high-quality pellet fuel from preselected biomass raw materials (i.e. Swedish willow species domesticated as energy crops; agricultural/food processing by-products). First, the combustion parameters of the respective energy willow species and of the biomass by-products were determined. Based on the results, one specific willow type and two of the by-products were selected as raw materials for pellet production. Preliminary calculations anticipated the technical availability of a potentially high-quality standard fuel.

Keywords: energy crops, pellet, alternative energy sources

Introduction

Pelleting is one of the most expensive ways of producing solid fuels from renewable resources. The energy demand of the process is relatively high, it takes 10–15% of the net energy content (net calorific value) of the pellet product itself. The question obviously arises: what makes pelletting viable?

While solid biomass fuels can be made cost-effective through the minimization of secondary processes, pellet production is complex and labour-intensive. For technical reasons, pellet fuels cannot be directly burnt even in high-temperature continuous energy systems (power stations, cement plants etc.) without a certain degree of fuel preparation. At small-scale discontinuous plants, controlled combustion is a necessary precondition for optimal operation. Smaller size and discontinuous operation makes the control of pellet-fuelled systems more difficult.

The size and shape of pellets is advantageous for relatively energy-efficient small-scale and medium-scale residential combustion equipments. Pellet storage requires about one-third of the net storage space of wooden chips, which is otherwise a relatively space-efficient fuel. Thus, the net energy content relative to storage space and material volume can be maximized, which is an important factor in designing heating systems e.g. of detached/semi-detached houses. Considering the ease of transport, the simplicity and convenience of fuel feeding (refill and dosage), there is no substantial difference between modern gas-fuelled and pellet-fuelled systems. On the other hand, safety risks related to storage and use are much lower for pellet than for gas.

Despite the relatively high price of pellets (47 to 95 HUF), pellet-fuelling is a competitive option for small-scale and medium-scale high-performance energy systems. When comparing the cost-efficiency of pellets and non-pelleted fuels, current and expected

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market trends should be considered, with special respect to steadily increasing fossil fuel prices. Today, pellet-based energy production is globally on the rise – though with considerable differences between the local economies and their capacity to adapt to the change.

Pellets combustion largely contributes to the utilization of biomass wastes, residues and by-products, thus to the reduction of GHG-emissions (particularly of CO₂) [1].

Heating pellets are cylindrical-shaped fuel products of a few millimeters length and diameter, primarily made from dried and compressed wood waste. Pellets combustion implies the burning of a natural, renewable-based biofuel that is free of artificial additives or chemical adhesives. (Wood shavings are usually held together by lignin, which is an organic constituent of wood). During the pelletizing process, the wood raw material is demoisturized in order to improve heat performance and to achieve smooth burning [2]. The technical specifications of pellets (dimensions, composition, raw materials, moisture and ash content etc.) are regulated by international standards.

Two main types of pellets can be distinguished:

- wood pellets: made from compacted heartwood sawdust and other wastes from sawmilling
- grass pellets (also called agri- or agropellets, non-woody pellets): made from herbaceous crops (straw, corn, energy grass, sunflower husk, chaff etc.)

The basic difference in the combustion parameters of the two is ash content. While wood pellets typically have an ash content of max. 1%, grass pellets yield 3–10% of ash – due to the variety of raw materials. This partly derives from the technology of crop harvesting, whereby considerable amounts of extraneous matter (dust, sand, dirt) get commingled with the plant parts. The net calorific value (lower heating value) of non-woody pellets varies over a wide range, and the raw materials are often mixed for better compressibility (biomass blending) [2].

1. The pellet production technology

1.1. Pre-treatment of the raw material

In case the moisture content of the raw material exceeds 15% m/m, preliminary drying is required. Proper drying is a key factor for production control and quality assurance. The total energy input of the production process largely depends on the initial moisture content of the biomass. Over 14–15% wetness, pelletizing is almost impracticable [3].

Upon arrival to the plant, the raw biomass regularly contains undesirable substances (stone, metals etc.). Extraneous matter is removed by magnetic separation or other cleaning techniques (e.g. sifting) prior to industrial processing. This step is best to be implemented before feed milling and refinement (pulverization). Next, the clean raw material is crushed and milled in a single- or double-step process – depending on the size and heterogeneity of the feed components. The ultimate aim is to obtain fine biomass powder with uniform particle size (0.5–1.5 mm is typically required for pelletizing) [3].

1.2. Pelleting

Pellets are commonly prepared with no external binding agents added. Preferably, lignin is used as a “natural glue” organically found in the wood material. In case of low lignin

content, however, some kind of cohesive substance or adhesive can be blended with the feedstock to facilitate pelletization and increase product density. Another method of quality improvement is the homogeneous mixing of by-products or the use of special biomass blends. The commingling e.g. of straw with pine bar, sawdust or wax improves compactness. Hardness, density and low moisture content are the most important pellet properties to be controlled [4].

Before actual extrusion, the feed mix is preconditioned with about 70 °C water-spraying. In some pelletization techniques, 1–2% hot water steam is used for preconditioning. During the heat-up process, the lignin content of the feed gets released, which contributes to the rearrangement of plant fibres. Thus, the pulverized biomass containing the plasticized lignin enters directly in the compression area of the pellet die (see Fig. 1). Here, the feedstock passes to the pelletizing chamber (i.e. the die-roller assembly) and gets pushed through the die holes by rotating press rollers. Once the pelletized material extrudes from the die holes, another dose of biomass mash enters the pellet die to be compressed by the rollers [3].



Figure 1. Pelleting equipment and the compression area of the pellet die

The factors influencing the quality and material properties of the final product are:

- the type and quality of the feedstock; pellet die compression ratio and the compression capacity of the pelleting press; die retention time (the specific time required by the feed spread on the die holes to bind together and form pellets); other intermittent processes,
- the friction and transmissivity of the pellet die,
- the surface properties of the press rollers and the pellet die (e.g. relief pattern),
- die hole geometry and L/D ratio (effective length [L] divided by the hole diameter [D]),
- the effective length of the die (the die thickness that actually performs work on the feed, thus determines the thickness of the material squeezed through the holes),
- compression ratio and rotational speed.

Feeds can be pelleted either in flat or in ring die mills. Complex, high-yield industrial pellet mills mostly apply rotating ring dies. Once the feedstock is introduced in the pelletizing chamber (mill drum or rotating drum), one or more rollers press/squeeze the material through the holes of the die at a defined compression rate. Then, the exposed pellet columns are torn up or crashed by a cutter (located on the other side of the die). Both types of pellet mills are supplied with differently patterned dies. Depending on the relief pattern

of the die (i.e. die thickness and hole size), pellet products of various length and diameter can be produced. The typical pellet diameter size is 6–8 mm [3–5].

The die and the rollers have supreme quality requirements, so that they would withstand extreme impact and wear. Besides material quality, compression ratio and the proper dosing of the feedstock are also decisive factors in production control. The ultimate aim is to reach high yield with low mechanical abrasion (i.e. of the mill assembly).

The compression process takes place at very high temperatures. Pressure rates are adjusted to feedstock type and other technical indicators. Generally, the higher the hardwood-content of the pelletized material is, the higher pressure rate is required for processing [3].

1.3. Cooling and packaging

The pellets exit the chamber in slightly plastic state at temperatures around 90 °C. A belt conveyor transports the pellets into a cooler. Air is pulled through the system to cool, dry, and harden the pellets making them resistant to spoilage and breakage. Thereby dust formation potential also gets reduced. Finally, the pellets are discharged into a shaker which functions as a fines and dust removal system. (Fines and dust are byproducts left from the pelleting process.) The finished products are either stored and sold bulk or packaged separately for sale. The residual particles recycled by the fines and dust collection system are redirected into the pelletization unit [3].

1.4. Pellet standards

In Hungary, wood pellets are qualified according to the European Standard (ENplus for fire pellets) and the certification scheme implemented in Germany – specifically:

- DIN 51731 “Pellets produced from untreated wood – HP 5”,
- ÖNORM M 7135 “Pellets produced from untreated wood or untreated bark, pellets and briquettes – HP1”,
- EN 14961-2: Solid biofuels – Fuel specification and classes – Part 2 – Wood pellets for non-industrial use.

2. Applied materials

The following section provides a detailed description of the raw materials used as biomass resources for pellet production.

2.1. SRC (*Short Rotation Coppice*) willow

Salix is a large genus of about 400–500 species of deciduous trees and shrubs (osiers) found primarily in the temperate zone of the Northern Hemisphere. Most willow species tolerate frost fairly well, therefore they are easy to cultivate in regions where winter is cold.

The purpose-bred varieties of *Salix* are suitable for energy cropping in short rotation coppice (SRC) systems. SRC planters propagate high-yield, fast-growing hybrids like *Salix viminalis* (common osier or basket willow), *Salix x smithiana* (typically white willow), and *Salix x dasyclados*. Compared to other woody perennials (e.g. poplar), willows produce the highest number of shoots per stool when coppiced (due to fast tiller development). Shrubby

Viminalis clones exhibit rapid growth and high yields in short rotation cycles (2–3 years). Tree-shaped species like *Salix alba* or *Salix rubens* have longer growing periods and become viable for harvesting in 5 to 10 years from coppicing – peak biomass occurs in the first 3–5 years of vegetation, though.

With proper timing and under optimal conditions, vigorous willow clones can be effectively propagated from woody stem cuttings (up to 100%). Plant regeneration from stool-shoots (or soboles) subsequent to harvesting is also satisfactory (see Fig. 2).

The establishment of SRC willow plantations is most viable in Hungarian wetland regions where inland water or groundwater-fed seasonal ponds preclude traditional crop cultivation – i.e. in the floodplains of rivers Tisza, Körös, Szamos, Bodrog [6]. Fertile plateaus – e.g. alluvial terraces and riverside meadows currently under arable crops – are also ideal for energy crop cultivation, due to extremely high soil productivity and high yield potential [7], [8], [9]. The breeding and plantation of willow clones for biomass energy is long since a proven method. Special cultivars are easy to propagate vegetatively (stem cuttings are ready to sprout roots), give a fast coppicing response (high growth rate) and produce stable yields every 2–3 years over generations [10], [11].

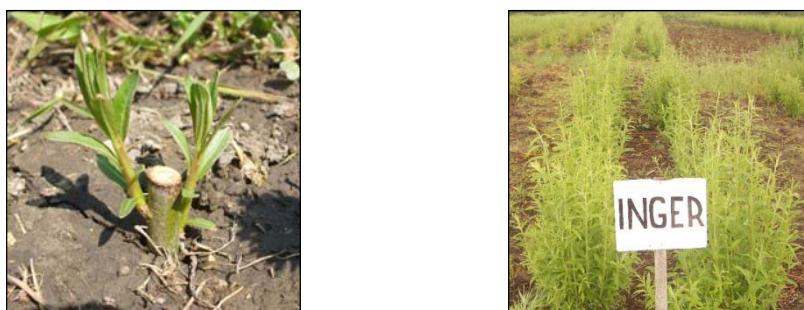


Figure 2. Propagation of SRC energy willow: mature stem cuttings and plantation stock (SW Inger)

In this study, three purpose-bred SW Salix varieties (SW Inger, dry soils; SW Tora and Sven, miscellaneous soils – each are available in Hungary) were selected as target species for the pelleting experiments.

Europe's largest SW seeds plant breeding station, Lantmännen SW Seed (run by Lantmännen Agroenergi AB, Sweden), looks back to more than 30 years of experience. Originally engaged in the selective cultivation of native species, Swedish professionals are now specialized in the targeted breeding of SRC willow crops by ways of genetic crossing and marker-assisted breeding. The ultimate aim of these techniques is to produce fast-growing, disease and pest-resistant plants with frost/drought tolerance and high biomass output. Today, Swedish willow clones are the most productive (show the best performance) of all European *Salix* varieties developed for energy cropping.

The following Swedish SRC willow clones are available in Hungary: Inger, Tordis, Tora, Torhild, Sven, Jorr, Gudrun, Olof and Doris. Laboratory and field testing by domestic researchers has shown the excellent performance and high adaptability of these willows to new ecological environments (compared to other European varieties). Due to environmental reasons, the hybrids Doris and Olof are nationally declared non-eligible, since these are the progenies of a Siberian basket willow (*Salix viminalis*), which is a non-native species in

Hungary. For the protection of domestic woodland, all promoters of exotic species are excluded from the beneficiaries of industrial forest plantation subsidies (in line with Hungarian forest resource management policies). Nonetheless, the domestication of Doris and Olof cultivars is not forbidden. Five other species, Tora, Tordis, Torhild and Sven prefer moderately wet habitats (with no slack water or residual waterbodies). Under such circumstances, these willows produce optimal dry matter yield. Sven exhibits good salt resistance, thus it is a potential candidate for root-zone waste water treatment. Inger is distinguished by its favourable properties like drought tolerance and high biomass output. Owing to the early start of the vegetation period, this domesticated clone has an outstanding capacity for weed suppression. Early bud burst is complemented with good frost tolerance: buds and shoots do not get damaged by mild winter frosts to 3 °C below zero. Inger cultivars can be harvested as soon as in November, before they enter into the phase of dormancy. The wetness of the freshly cut biomass is 44–52%. (Subsequent to harvest, four to six weeks of drying is necessary to reach the moisture level [<35%] required for cost-efficient transport). Yield stability is the most impressive trait of Inger. It is based on the good eco-adaptability of the clones to local environmental volatilities (e.g. drought, seasonal floods or inland water) [12].

2.2. Nutshell

As a by-product, cracked nutshell is extremely hard, firm, sharp-edged, non-perishable and retains quality over an extended period of time. It is neither toxic nor in any ways harmful or dangerous to human health; it does not cause adverse effects if swallowed or rubbed into the skin. Nutshell is non-reactive with either basic or acidic media. The woody shell consists of a solid superstructure of cellulosic fibres, where lignin and hemicellulose function as filling and binding materials. Nutshell waste is reutilizable, organic and biologically neutral, it naturally decomposes [13].

Characterized by low moisture content and fairly high heating value (18–20 MJ/kg), nutshell is considered a valuable biomass source.

2.3. Corn stover

Worldwide, corn stover is increasingly being harvested as a feedstock for biomass fuel production. The energy use of corn stover provides an economic benefit (i.e. a new source of income) for inland corn grain farmers and contributes to the commitment of the individual states to reach renewable energy targets. In present-day agricultural practice, however, corn stover is generally left on the fields to protect the soil from erosion and deflation, facilitate water retention and provide nutrient supply (soil fertilisation) [14].

In Hungary, corn stover is the second largest source of vegetable by-products (after straw). About 90% of the total amount of corn growing by-products is stalks and leaves (corresponding to an energy content of about 90 PJ per year). Specially equipped combines (forage choppers) are used for the cutting, shredding and baling of corn stover. A great obstacle to viable harvest, storage and industrial processing is the wetness of the raw material. The moisture content of freshly cut corn stover ranges from 30 to 70%, therefore special treatment and storage is required to avoid maintenance difficulties and/or quality deterioration [8]. Cost-efficient commercial drying techniques, which would facilitate the conversion of crop residues into biofuel are not yet available.

Supposing that the stored biomass has an optimal moisture content of 12–20% m/m, the lower heating value of the fuel amounts to 13–14 MJ/kg, which is an attractive combustion parameter.

2.4. Sunflower seed shell

Sunflower shells is the residues remaining from the commercial hulling and separation of harvested sunflower seeds. If heating properties are considered (low moisture content, high calorific value), this biomass gives an outstanding feedstock for bioenergy production [9]. Sunflower seed shells is generated as a co-or by-product from the food processing industry (particularly by vegetable oil refining), therefore, with proper bilateral cooperations between the production partners, it is easy to "collect" and is regularly available in large quantities. Even in Hungary, there are several good examples of successfully installed pellet-fuelled heat recovery equipments fed exclusively by sunflower hull pellets, mostly operating in vegetable oil refineries or other small-scale plants. The state-of-art systems, however are not entirely free of operational problems.

3. Methods

As described in the previous section, the research samples were obtained from a variety of sources, including short rotation wooden perennials from energy plantations, agricultural by-products and industrial wastes. Before pelleting, the combustion parameters of these raw materials were tested. The methodology and the test results are presented below.

3.1. Ultimate analysis

Elemental or ultimate analysis encompasses the quantitative determination of the basic chemical constituents (carbon, hydrogen, sulphur, nitrogen and oxygen) found in organic substances. The chemical composition of fuels is a key factor in calculating higher and lower heating values (HHV/LHV), estimating actual heating performance and optimizing the combustion process for the respective feed.

Carbon-, hydrogen- and oxygen-content primarily define the combustion properties and thermal behaviour of fuels. Percentages of nitrogen and sulphur are, on the other hand, associated with environmental impacts and corrosion risks.

There are several methods available for the determination of chemical composition. Most of these include the thermal conversion (i.e. the complete oxidation) of the fuel samples and the componental analysis of the flue gas formed from the process. In this study, a Carlo Erba EA 1108 type elemental analyser (with a software-based data acquisition system) was used for the measurement of the C-, H-, N- and S-content in the respective fuels – in line with the principles and methodology suggested by the international standards (ISO, DIN, CEN).

3.2. Moisture

When testing biomass samples, two forms of moisture are a matter of interest: intrinsic moisture – the one contained without the influence of weather – and extrinsic moisture, which is influenced by weather conditions during harvesting.

Total moisture content (W_t) can be determined with single-step and double-step methods, the latter including raw and hygroscopic mass measurements. In this study, a single-step drying method (oven-dry method) was chosen for the determination of total moisture contained by the fuel samples – as recommended in the respective standard (standard No. 24000-23-1977 by MSZ). The final results were calculated with the following formula:

$$W_t = \frac{m_1}{m} \cdot 100, \% \text{ m/m} \quad (1)$$

where

m_1 weight loss (of the sample) on drying, g;
 m the initial weight of the sample, g.

3.3. Ash content

Ash is the solid burning residues left from the complete combustion of a fuel. It comes from the mineral components and other inorganic matter originally present in the fuel.

Three measurements were executed for each fuel sample, following the protocol provided in the Standard Analytical Method No. MSZ ISO 1171. This test method covers the determination of ash (A), expressed as the percentage of residue remaining after dry oxidation in closed chamber at 815 ± 10 °C (with prefixed, constant air flow rate). All results are reported relative to the oven dry weight of the sample, according to the formula:

$$A = \frac{m_3 - m_1}{m_2 - m_1} \cdot 100, \% \text{ m/m} \quad (2)$$

where

m_1 the weight of the crucible, g;
 m_2 the initial weight of the crucible and the sample together, g;
 m_3 the weight of the crucible and the ash produced, g.

3.4. Determination of higher heating value (HHV) and lower heating value (LHV)

Calorific tests were performed using a Parr 6200 type calibrated isoperibol oxygen bomb calorimeter. The higher heating values (energy equivalent values) of the tested fuel samples were automatically computed by the data processing system. The principle of the measurement was based on a substitution procedure in which the heat obtained from the sample was compared with the heat obtained from combustion of a similar amount of benzoic acid (as standardizing material) whose calorific value was known. Measurements were obtained by burning the representative samples in high-pressure oxygen atmosphere within a metal pressure vessel or “bomb”. The energy released by this combustion was absorbed within the calorimeter and the resulting temperature change within the absorbing medium was noted. The heat combustion of the sample was calculated by multiplying the temperature rise in the calorimeter by a previously determined energy equivalent (or heat capacity) determined from previous tests with a standardizing material. Corrections had to be applied to adjust these values for the heat transfer occurring in the calorimeter, as well as for the side reactions which are unique to the bomb combustion process.

$$HHV = \frac{V(t_m - t_0 + c) - \Sigma b}{G}, \text{ kJ/kg} \quad (3)$$

where:

- V heat capacity of the bomb (relative to water), J/°C;
- t_0 initial temperature of the measurement, °C;
- t_m final temperature of the measurement, °C;
- c correction factor for heat transfer between the calorimeter and its environment, °C;
- Σb standard deviation or summated heat value from external processes (side reactions), J;
- G sample weight, g.

In the calculation of V and Ho, the Regnault–Pfaundler method was applied to determine the proper correction factor for heat transfer, [c].

Three experiments were developed for each sample to secure data reproducibility. For the determination of the lower heating value (net heating value), the following formula was used (as given by the pertinent standard):

$$LHV = HHV - 24,49278 \cdot (9 \cdot H + W_t), \text{ kJ/kg} \quad (4)$$

where

- HHV higher heating value (as defined above), kJ/kg;
- H weight percent hydrogen in the sample (as specified by MSZ 24000/11), % m/m;
- W_t moisture content of the samples (“total moisture” for wet samples, “0” for dry samples), % m/m.

4. Results and discussion

4.1. Ultimate analysis

The results obtained from ultimate analysis are shown in Table 1. Out of the three main components of solid fuels (carbon, nitrogen, oxygen), two were measured (C, N).

Table 1
Ultimate analysis data for SRC willow and biomass wastes

Sample	C-content wet % (m/m)	H-content. wet % (m/m)	N-content wet % (m/m)	S-content wet % (m/m)
SW Inger	47.81	6.46	0.18	<0.01
Tora	47.96	6.63	0.22	<0.01
Sven	49.37	6.83	0.13	<0.01
Nutshell	50.94	6.67	0.71	<0.01
Corn stover	46.98	6.29	0.21	<0.01
Sunflower seed shell	47.45	6.32	1.25	<0.01

The wet biomass samples contained about 47.4–50.9% m/m of C; 6.2–6.8% m/m of H and 0.1–1.2% m/m of N. The sulphur-content stayed below the lower limit of detection

(0.01%). Most values fell approximately in the same range, with a prominent difference observable in the high percentage of N in sunflower seed shells.

4.2. Proximate analysis

For reasons of reproducibility, three experiments were performed on each fuel sample. The results are presented in Table 2 (the values are the mean averages of 3 measurements).

Table 2
Proximate analysis data for energy crops and industrial wastes

Fuels	Moisture (% m/m)	Ash (% m/m)	HHV (MJ/kg)	LHV (MJ/kg)
SW Inger	39.64	0.63	19.23	16.83
Tora	39.33	0.65	18.51	16.09
Sven	37.66	0.64	18.94	16.51
Nutshell	12.76	1.12	18.93	17.15
Corn stover	17.35	6.51	16.70	14.89
Sunflower seed shell	13.15	2.54	18.75	17.04

As seen, the total moisture content of the tested SRC willow and biomass samples tend to vary over a wide range (12.76–39.64% m/m). Moisture is a critical parameter in designing suitable combustion technologies and proper combustion units tailored for these fuels. Note should be taken that the respective willow samples were tested within 1 week from cutting, without any kind of pre-treatment. This accounts for their exceptionally high initial moisture content. On the other hand, all other biomass sources were relatively dry, even corn stover contained moisture to less than 20% m/m.

SRC willow is proven to yield very low amounts of ash when burnt. Thus, it is the prime source for pellet production. The ash content of other biomass sources is largely dependent on material composition. Degradable dry matter content indicates whether the given raw material can be effectively admixed with the feedstock to make high-quality pellets. Based on the results, the applicability of corn stover is not convincing.

SRC willows are characterized by uniformly high HHV. Out of the tested biomass waste samples nutshell and sunflower seed shell were found to have satisfactory HHVs for quality pellet fuel production.

4.3. Hypothetical pellet mixtures

Of the tested biomass resources, SW Inger (SRC willow), nutshell and sunflower seed shells (biomass by-products) were selected as potential applicants for experimental biofuel pelleting (relatively low moisture and ash content).

Prior to the actual experiments, hypothetical pellet mixtures were compiled from the data measured for the distinctive constituents. The mixture rates with the calculated fuel characteristics are presented in Table 3. The table was used as a tool in the preliminary selection of the best possible mixture with the most optimal combustion parameters.

Table 3
Proximate analysis data for the hypothetical pellet mixtures

Fuels	Moisture (% m/m)	Ash (% m/m)	HHV (MJ/kg)	LHV (MJ/kg)
90% m/m SW Inger + 10% m/m Nutshell	36,952	0,679	19,2	16,86
80% m/m SW Inger + 20% m/m Nutshell	34,264	0,728	19,17	16,89
70% m/m SW Inger + 30% m/m Nutshell	31,576	0,777	19,14	16,93
60% m/m SW Inger + 40% m/m Nutshell	28,888	0,826	19,11	16,96
90% m/m SW Inger + 10% m/m Sunflower seed shell	36.991	0.821	19.18	16.85
80% m/m SW Inger + 20% m/m Sunflower seed shell	34.342	1.012	19.13	16.87
70% m/m SW Inger + 30% m/m Sunflower seed shell	31.693	1.203	19.09	16.89
60% m/m SW Inger + 40% m/m Sunflower seed shell	29.044	1.394	19.04	16.91

While most hypothetical mixtures are characterized by relatively low ash content (>1%), the addition of excessive amounts of sunflower seed shell to the feedstock results in a drastic increase in ash production. Higher heating values invariably stay above 19 MJ/kg, which is considered very good.

Conclusions

The ultimate aim of this research is to produce high-quality pellet fuels from SRC energy willow and biomass by-products. In the first step, the combustion analysis of three SW *Salix* clones and three distinctive biomass materials was performed. Considering (low) ash content and (moderately high) heating value, the results obtained for nutshell and sunflower seed shells seem most promising. With regard to the combustion properties of the hypothetical pellet mixtures, nutshell appears to be the preferred choice. The high oil content of this biomass might even contribute to the compactness and density of the pellets.

Based on the reported data, the availability of nutshell and sunflower seed shell resources is virtually unlimited. In 2011, more than 24 tonnes of nutshell wastes were generated by industrial producers in Hungary. This quantity represents a year of poor agricultural performance (when merely half of the expected yields were actually harvested) due to extreme summer heat and drought. Given the steady expansion of domestic walnut plantations and assuming a normal year, the estimated total amount of nutshell waste may reach 48 tonnes per year.

The next research step involves the preparation and testing of various pellet mixtures. Combustion analysis would be completed with ash characterization (compositional data,

ash fusion characteristics) in order to provide data for the pelleting industry, including pellet stove manufacturers.

Acknowledgements

This research was carried out in the framework of the Center of Excellence of Sustainable Resource Management at the University of Miskolc.

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