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The potential use of invasive plant species as solid biofuel by using binders

L. Zihare,* R. Soloha and D. Blumberga

Riga Technical University, Faculty of Electrical Engineering, Institute of Energy Systems and Environment, Āzenes iela 12/1, LV-1048 Riga, Latvia
*Correspondence to the author: lauma.zihare@rtu.lv

Abstract. The aim of the current research is to find sustainable pellet resources that are not made from forestry, agricultural materials, or food products. Evaluation has been carried out by experimentally determining the biofuel parameters of two invasive plant species. In comparison to the process of finding a new application, their use in the production of solid biofuel pellets would not require additional investment for the construction of a new pellet production plant. The article's hypothesis suggests that biofuel parameters for invasive plant species are sufficient for the production of solid biofuel and that their properties can be improved by binders that are available worldwide in the form of residues.
The experiment was carried out for two invasive plant species that are widespread in Latvia – *Heracleum sosnowskyi* Manden and *Solidago canadensis* L. The binders used include potato peel waste and spent coffee grounds. All of the tests have been carried out according to ISO standards on biofuel testing. Results show that *H sosnowskyi* is more suitable for solid biofuel than *S canadensis* as it has a higher calorific value and an ash content that is two times lower – 3wt%. Coffee grounds are a suitable binder because they increase calorific value.
The type and amount of binders partly confirms the hypothesis, since both binders reduced the amount of ash in pellets. Further research is needed to carry out pellet durability tests. It is also necessary to carry out an economic analysis in order to evaluate how beneficial it may be to use *H sosnowskyi* as a solid fuel in existing pellet production plants, thereby avoiding large initial investments and not encouraging the cultivation of invasive plant species.

Key words: *H sosnowskyi*, *S canadensis*, spent coffee grounds, potato peel waste, pellets.

INTRODUCTION

Currently one of the main challenges faced by the pellet industry is in the limitation of raw materials (Emadi et al., 2017). In the energy sector, one of the fastest growing markets is pellet production and consumption (Gravelsins et al., 2017). For the most part, pellets are prepared from wood as a raw material, but in order to be able to satisfy growing demand new materials have to be integrated into the production processes. Existing research offers non-woody materials such as herbaceous biomass, fruit biomass, and aquatic biomass (Konrád et al., 2017). In comparison with wood biomass, non-wood materials have a higher compound variation which creates a certain degree of challenge for the pellet production industry. Therefore, the quality of the raw material is important (Konrád et al., 2017).

Existing non-woody materials are agricultural biomass, wheat straw, rapeseed straw, maize straw, and others (I Niedziiolka et al., 2015). Research for substitute solid biofuel availability and energy sources concludes that herbaceous biomass has the potential for energy production (such as common reed and *H sosnowskyi*) (Beloborodko et al., 2013); therefore the focus in this study is on herbaceous biomass, which is available, and which is widespread and unused in Latvia. Agricultural residues are abundant and are an inexpensive source of renewable energy (Lu et al., 2014). Agricultural residues, such as straw, do not contain an adequate amount of natural binding components – lignin, protein, starch, or water soluble carbohydrates. One solution is to de-bond lignocellulosic matrix structures that free the lignin. However, that involves pre-treatment (including the use of chemicals, additives, a microwave, a steam explosion, or other methods). Another solution is to add a binder, in that way improving pellet durability and strength (Lu et al., 2014). Various types of natural binders are used for the improvement of pellet durability, such as rapeseed flour, coffee meal, bark, lignin powder, pine cones (Ahn et al., 2014), potato flour, potato peel residue, lignosulphonate (Kuokkanen, 2013), and others (Tarasov et al., 2013). The most important aspects are to find a binder that is of a low cost, does not require additional treatment, and is environmentally friendly.

Raw material selection is necessary when it comes to finding a sustainable solid biomass fuel, one which is not used in the production of any higher added value product. The aim of this study is to find good quality non-woody raw materials for solid biofuel. This has been managed by creating a methodology with sustainability criteria regarding solid biofuel raw materials and natural binders, as well as carrying out experimental analyses on selected biomass and binders.

MATERIALS AND METHODS

Methodology is focused on the selection of raw materials that can be used as a solid biofuel but which are not used in the forestry, agriculture, aquaculture, or food industries. Sustainability criteria are determined to select appropriate materials and binders, as well as to find low costs and, preferably, residue and/or waste bioresources. At first, samples were prepared with and without binders. Binders were used in the same proportion for each sample. The determination of main solid biofuel parameters (ash and moisture content, and calorific value) allowed for an evaluation of the quality of raw materials, the binder, and the mixed pellet. Materials with higher calorific values, and a lower ash and moisture content, were selected for further testing. In further sample preparation, different binder proportions are used (10w-%, 30w-%, and 50w-%). The parameters being tested are the same as previously. If the calorific value increases, the ash content remains the same or decreases, and the moisture content is lower than 10w-%, then the solid biofuel and binder can be classified as being justified. If the changes are significant and without clear tendency, more samples need to be tested in different proportions in order to discover the optimum proportion and results.

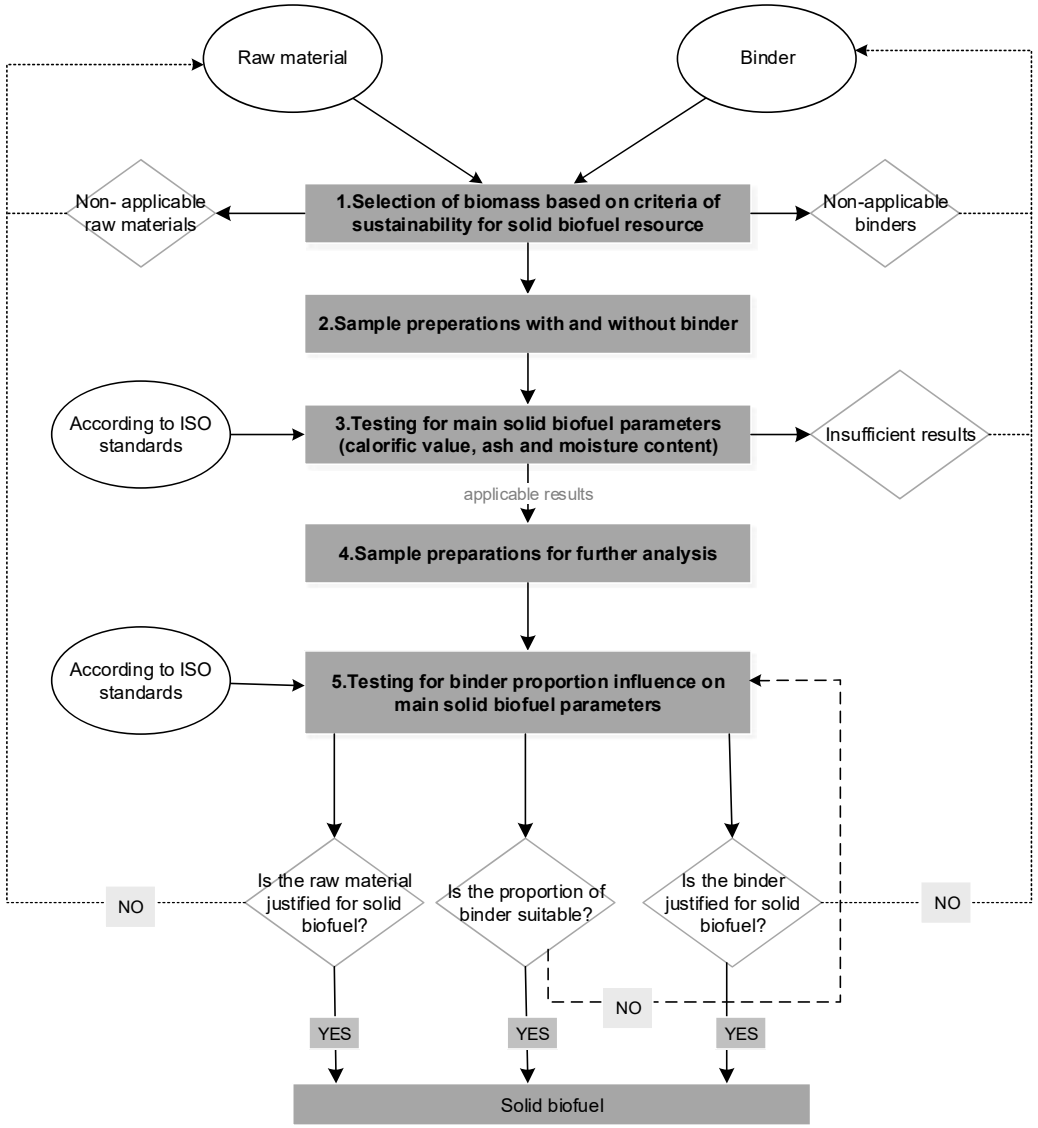

Figure 1. The validation of the resource-methodology algorithm.

Fig. 1 shows the methodology algorithm for resource validation as solid biofuel. The steps and criteria selected restrict the selection of biomass and biofuel. The methodology case study is conducted on invasive species.

1. The selection of biomass based on sustainability criteria for solid biofuel resources

After selecting raw materials and binders in accordance with the sustainability criteria, two raw materials and two binders have been selected for sample preparation and further analysis.

The sustainability criteria for the raw materials and binder selection for solid biofuel are as follows:

- non-woody resources;
- non-agricultural resources;
- resources that are not used in aquaculture;
- no fertiliser or additional water needed;
- a resource that is not used in the food industry;
- a bioresource (not fossil fuel);
- residue or waste that remains unused elsewhere;
- an available or local resource (which corresponds to geographical location and climate zone)
- a low cost resource;
- a resource that is not used in the production of a high added value product in the specific location (country);
- a positive impact on the environment and climate.

Invasive species that have invaded agricultural land and meadows meet the eligibility for sustainability criteria given above. Two of the most invasive plant species in Latvia have been selected for the case study: *Solidago canadensis L* and *Heracleum sosnowskyi* Manden. First of all, both have invaded agricultural land and meadows and are a waste product with no added value in Latvia. Secondly, these invasive species can grow on low nutrition land with no fertilisers or additional water. Thirdly, they are not used in the food industry and are available at a low cost. Mowing and utilising these plants to produce a valuable product would help to control their spread, as well as improving biodiversity. Two possible binders have been selected: potato peel waste and spent coffee grounds. The selected binders also correspond to the critera of sustainability.

2. Sample preparation

Raw materials have been collected in Riga. *H sosnowskyi* samples were collected at the end of October (2017) and *S canadensis* samples were collected at the end of August (2017). Plant materials were initially pre-dried in the laboratory at ambient conditions and afterwards dried completely in a dryer for eighteen hours at 105 °C. Afterwards, the samples were ground down in a mill (Vibrotehnik PM120) into particles smaller than 1mm in diameter. To ensure that particle size was less than 1mm, the mill contained a sieve with an aperture size of 1 mm.

The binders were air-dried for a week. The size of spent coffee grounds was already < 1 mm. This has been double-checked using the Retsch AS 400 sieve, with a sieve aperture size of 1mm. Potato peel waste was also ground down in the mill.

The first eight samples were prepared as follows: pure *S canadensis* (Sc), pure *H sosnowskyi* (Hs), pure coffee grounds (CG), pure potato peel waste (PPW), and S with 6wt% CG, S with 6wt% PPW, H with 6wt% CG, and finally H with 6wt% PPW.

All of the samples were prepared in accordance with the ISO (International Organisation for Standardisation) ISO 14780 standard.

3. Testing main biofuel parameters

The main biofuel characteristics were tested according to ISO standards for biofuel testing: ash content, moisture content, and calorific value.

3.1. Ash content

Ash content analysis has been carried out according to the ISO 18122 standard. The ash content has been calculated by taking into account the initial mass of the test portion and the mass of the ash that remained after the sample had been combusted. To prevent any absorption of moisture from the atmosphere, dishes containing the ash were kept in a desiccator.

The ash content was calculated according to Eq. (1):

$$A_d = \frac{(m_3 - m_1)}{(m_2 - m_1)} \times 100 \times \frac{100}{100 - M_{ad}} \quad (1)$$

where m_1 – mass of empty dish, g; m_2 – mass of dish plus the test portion, g; m_3 – mass of dish plus ash, g; M_{ad} – moisture content of the test portion used for a determination of ash content, w-%.

3.2. Moisture content

The sample was kept in air-tight plastic bags (according to EN 14778). The moisture content of the general analysis sample has been determined according to ISO 18134-3 (LVS EN ISO 18134-3:2016 Solid biofuels – Determining moisture content – oven dry method – Part3: moisture in a general analysis sample (ISO 18134-3:2015), 2016). The sample was dried in a drying oven at 105 °C.

It was assumed that the sample does not lose moisture during the preparation of the test portion. The mass of the test portion was in the range of 0.8–1.1 g.

Following sample preparation, a clean and empty weighing dish with its lid was dried at (105° ± 2) °C and then cooled to room temperature in a desiccator. The test portion was then placed in the dried dishes and dried for a period of one hour without its lid at (105° ± 2) °C, after which each dish with a sample and lid was weighed. In total each test portion was dried three times (three periods of one hour) to ensure that the sample dried completely.

$$M_{ad} = \frac{(m_2 - m_3)}{(m_2 - m_1)} \times 100 \quad (2)$$

where m_1 – mass of the empty dish plus lid, g; m_2 – mass of the dish, lid and test portion before drying, g; m_3 – mass of the dish, lid and test portion after drying, g.

3.3. Calorific value

A calorific value analysis was carried out according to the ISO 18125 standard. The experiment was handled in isoperibolic conditions, and the reference temperature was 30ºC (*LVS EN ISO 18125:2017 Solid biofuels – a determination of calorific value (ISO 18125:2017)*, 2017).

Due to the low density of solid dry biofuels, it is necessary to form a pellet in order to test the calorific value. The biofuel sample was pressed in a manual pellet press (IKA C21) to produce a compact and dense test piece weighing 1.0g ± 0.2 g.

The calculation for the gross calorific value of the dry mass (at a constant volume) is as follows:

$$Q_a^d = H_0 - \frac{Q_{N,S+} Q_S}{m} \quad (3)$$

Q_a^d – gross calorific value at a constant volume, J g^{-1}; m – mass of sample, g; $Q_{N,S}$ – heat correction, considering the formation of nitric acid, J; Q_S – heat correction, considering the formation of sulphuric acid, J; H_0 – gross calorific value of the analysed fuel, J g^{-1}.

The repeatability limit for non-wood solid biofuels is 140J/g (*LVS EN ISO 18125:2017 Solid biofuels – a determination of calorific value (ISO 18125:2017)*, 2017).

$$Q_S = 57 \cdot S^d \cdot m_s, \quad (4)$$

where S^d – sulphur content in the analysed sample (on a dry basis), %.

$$Q_{V,gr,d} = Q_{V,gr} \cdot \frac{100}{100 - M_{ad}}, \quad (5)$$

$Q_{V,gr,d}$ – gross calorific value of dry mass at a constant volume, J g^{-1}; M_{ad} – moisture content of the general analysis sample, wt%.

$$Q_{p,net,d} = Q_{V,gr,d} - 212.2 \cdot H^d - 0.8 \cdot (O^d + N^d), \quad (6)$$

where $Q_{p,net,d}$ – net calorific value of the dry mass at a constant pressure, J g^{-1}; H^d – hydrogen content in the analysed sample (on a dry basis), wt%; O^d – oxygen content in the analysed sample (on a dry basis), wt%; N^d – nitrogen content in the analysed sample (on a dry basis), wt%.

$$q_{p,net,ar} = q_{p,net,d} \cdot (1 + 0.01 \cdot M_{ar}) - 24.42 \cdot M_{ar}, \quad (7)$$

where $q_{p,net,ar}$ – net calorific value for the sample as received at constant pressure, J g^{-1}; M_{ar} – total moisture content, wt%.

4. Sample preparations for further analysis

After selecting samples for further analysis, new samples were formed using the best material (a higher calorific value shown for one of the species and increasing calorific value for the binder), which contained 10wt%, 30wt%, or 50wt% of binder accordingly.

5. Testing for binder influence. Validation

Validation for whether the resource and binder is justified as a solid biofuel is based on the results or calorific value, ash content, and moisture content. For resources the justification is based on calorific value – that closest to wood's calorific value, lower ash content, and lower moisture content. Binder justification is either based on increasing calorific value or it can remain the same if it does not change other parameters, ie. if the binder that is added serves to decrease the calorific value then it is not justified. A binder is also justified in terms of decreasing ash content. If adding a binder to the main resource means that it increases the ash content, then a binder is not justified and a different binder will have to be selected. By adding the binder, the moisture level will increase, but it is important to determine the optimum amount of binder added, so that the moisture level is also optimised.

RESULTS AND DISCUSSION

The results of tests involving moisture content (wt%), ash content (wt%), and calorific value (MJ kg^{-1}) have been determined during analysis. In order to be able to get reliable results for the calorific value, there is the necessity of determining and calculating the chemical composition of each sample. All of the results are corrected

with chemical composition values for carbon (C), hydrogen (H), nitrogen (N), and sulphur (S).

The chemical composition (*C, H, N, S)* of the pure materials – coffee grounds (CG) (Somnuk et al., 2017), potato peel waste (PPW) (Krus & Lucas, 2014), and *S canadensis* (Sc) (Ciesielczuk et al., 2016) were taken from the available literature, *H sosnowskyi* (Hs) from experimental analysis by chromatograph, and mixed samples were calculated according to the proportions being mixed – see Table 1. Samples that were tested after selecting a suitable material and binder were: *H sosnowskyi* and spent coffee grounds accordingly. The proportions are as follows: Hs 90wt%:CG 10wt%, Hs 70wt%:CG 30wt% and Hs 50wt%:CG 50wt% and were calculated accordingly. According to EN plus pellet quality requirements for wood pellet quality classes, the N and S amount is very important for solid biofuel quality. The highest acceptable N amount is 1.0wt% and for S it is 0.05wt% (European Biomass Association (AEBIOM), 2015). If the aim is to compete with or to achieve qualities which are similar to wood, then no more than 30wt% of CG binder can be added.

Table 1. Chemical composition of the samples

	CG	PPW	Sc	Hs	Sc, PPW 6wt%	Sc, CG 6wt%	Hs, PPW 6wt%	Hs, CG 6wt%	Hs, CG 10wt%	Hs, CG 30wt%	Hs, CG 50wt%
C	52.95	43.90	44.80	46.52	44.75	45.29	46.36	46.91	47.16	48.45	49.74
H	6.76	7.20	6.46	5.79	6.50	6.48	5.87	5.84	5.88	6.08	6.27
N	2.10	0.80	0.37	0.59	0.40	0.47	0.60	0.68	0.74	1.04	1.35
S	0.12	0.10	0.20	0.00	0.19	0.19	0.01	0.01	0.01	0.04	0.06

Key: Sc, PPW 6wt% – *S canadensis* (94wt%) mixed with 6wt% potato peel waste; Sc, CG 6wt% – *S canadensis* (94wt%) mixed with 6wt% coffee grounds; Hs, PPW 6wt% – *H sosnowskyi* (94wt%) mixed with 6wt% potato peel waste; Hs, CG 6wt% – *H sosnowskyi* (94wt%) mixed with 6wt% coffee grounds.

According to the third step of the methodology algorithm, the first sample results are obtained for two species and two binders; further selection is carried out for species with a higher calorific value, and a lower ash and moisture content. The binder is further selected by positive changes in tested samples.

In Fig. 2 changes in biofuel parameters are shown for a pure materials sample (base sample – no binder added). The *H sosnowskyi* and PPW (Hs, PPW 6wt%) sample shows an increase in moisture content, and a small decrease in ash content and calorific values. *S canadensis* with both binders (PPW and CG) show a decrease in all parameters. Only *H sosnowskyi* with a CG binder shows an increase in calorific value and no important changes in moisture and ash content. Therefore, *H sosnowskyi* and CG were selected for further testing using different proportions of the binder. There are no similarities between either of the binders or their effect on biomass parameters; for example, the PPW binder decreases moisture for one biomass, but increases it for the other. Therefore further experiments with other types of biomass are preferable.

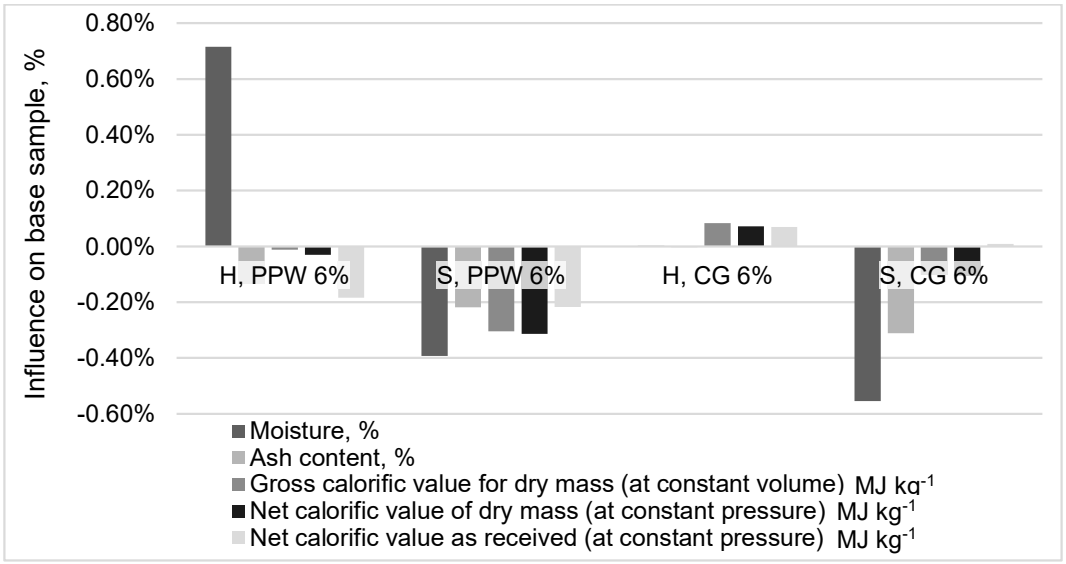

Figure 2. Biofuel parameter changes by binder type.

For the final results for all samples, see Table 2, which shows that the highest calorific value is for the pure coffee ground sample, whilst the lowest is for the potato peel waste. Potato peel waste has the highest moisture content. Thanks to these results, potato peel waste is proven not to be a very suitable binder. *Solidago canadensis* has a high moisture and ash content and, although the calorific value is good for non-woody material, *Heracleum* showed better results in all parameters and is therefore selected for further experiments.

Table 2. The results for solid biofuel parameters in all samples

Sample	Moisture (%)	Ash content (%)	Gross calorific value* (MJ kg^{-1})	Net calorific value ** (MJ kg^{-1})	Net calorific value *** (MJ kg^{-1})
Sc, 0%	7.3%	6.8%	18.24	16.84	15.43
Hs, 0%	3.1%	3.4%	19.45	18.19	17.56
Hs, PPW 6%	3.8%	3.3%	19.44	18.16	17.37
Sc, PPW 6%	6.9%	6.6%	17.94	16.52	15.22
Hs, CG 6%	3.1%	3.4%	19.53	18.26	17.63
Sc, CG 6%	6.7%	6.5%	18.14	16.73	15.44
Hs 90%, CG 10%	3.7%	3.4%	19.64	18.36	17.59
Hs 70%, CG 30%	4.8%	3.1%	20.42	19.10	18.07
Hs50%, CG 50%	6.1%	2.9%	21.09	19.73	18.39
CG 100%	9.2%	2.3%	22.73	21.27	19.08
PPW100%	15.9%	5.8%	17.90	16.33	13.36

* for dry mass at a constant volume; ** for dry mass at a constant pressure; *** for a sample as received at constant pressure.

Fig. 3 illustrates how the added amount of CG binder (10wt%, 30wt%, 50wt%) influences biofuel parameters. In comparison to a pure Hs sample, *H sosnowskyi* with CG increases calorific value (the gross calorific and net calorific value of dry mass; the

net calorific value as received), lowers ash content, and increases moisture content. When analysing all parameters the optimal moisture content, ash content, and calorific value for *H sosnowskyi* shows no more than 30wt% CG binder.

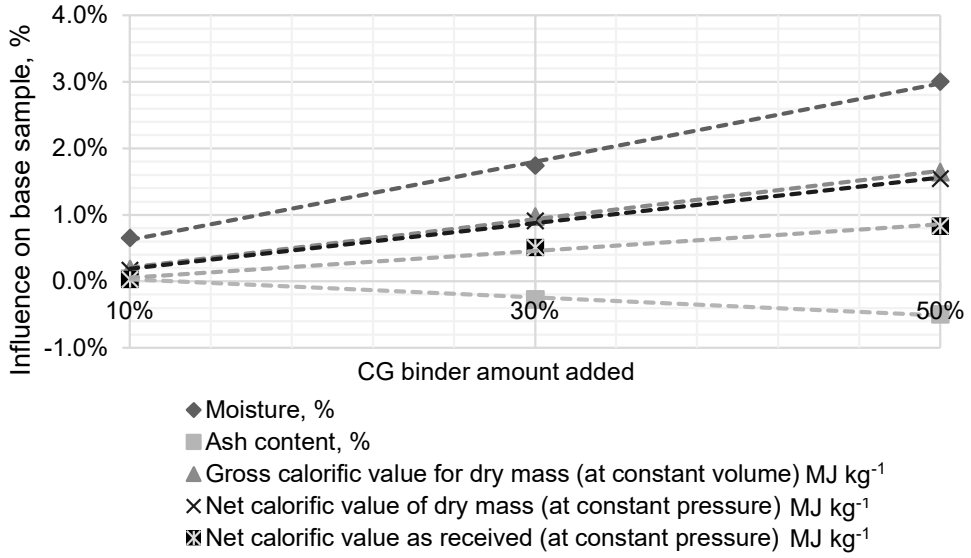

Figure 3. Biofuel parameter changes by different proportion of CG binder.

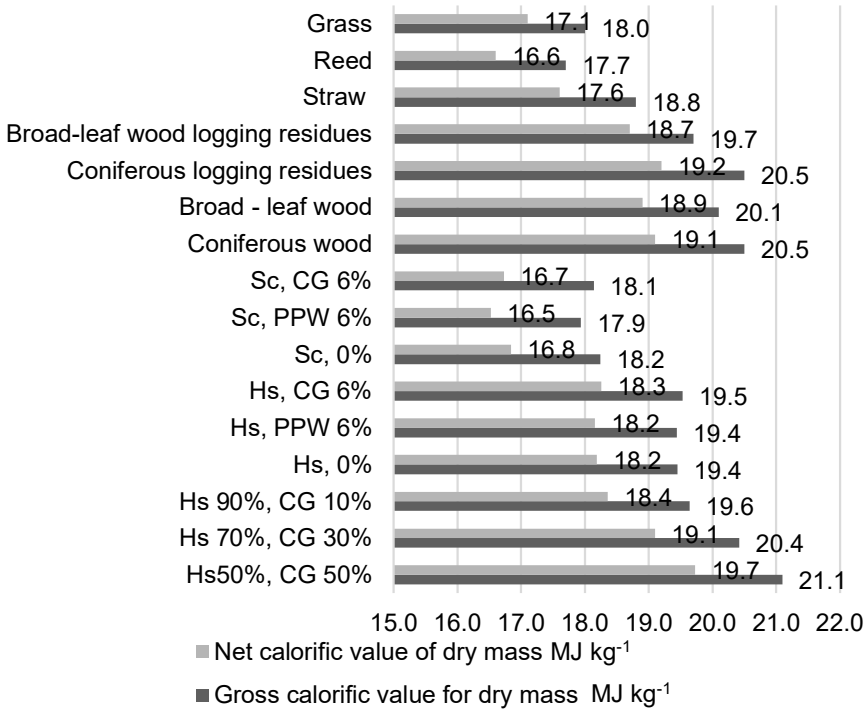

Figure 4. A comparison of calorific values between existing solid biomass fuels and tested samples.

In order to determine the quality of the tested sample, a comparison with other existing solid biomass fuels was carried out. Typical values have been taken from the ISO 17225-1:2014 standard. The main values taken for the comparison are grass (in general), virgin reed canary grass (summer harvest), virgin straw materials from wheat, rye, and barley, virgin wood logging residues for coniferous and for broad-leaf wood, and virgin wood materials for broad-leaf wood and coniferous wood.

The results for all *Solidago* samples – see Fig. 4 – corresponds to reed and grass calorific values with and without binders; however *Heracleum* is competitive with broad-leaf logging residues. Moreover, mixed samples are even comparable to the results for coniferous logging residues, broad-leaf wood, and coniferous wood. The best results are for the *Heracleum* sample with 50wt% coffee grounds. To determine the optimal proportion, ash content should also be taken into account.

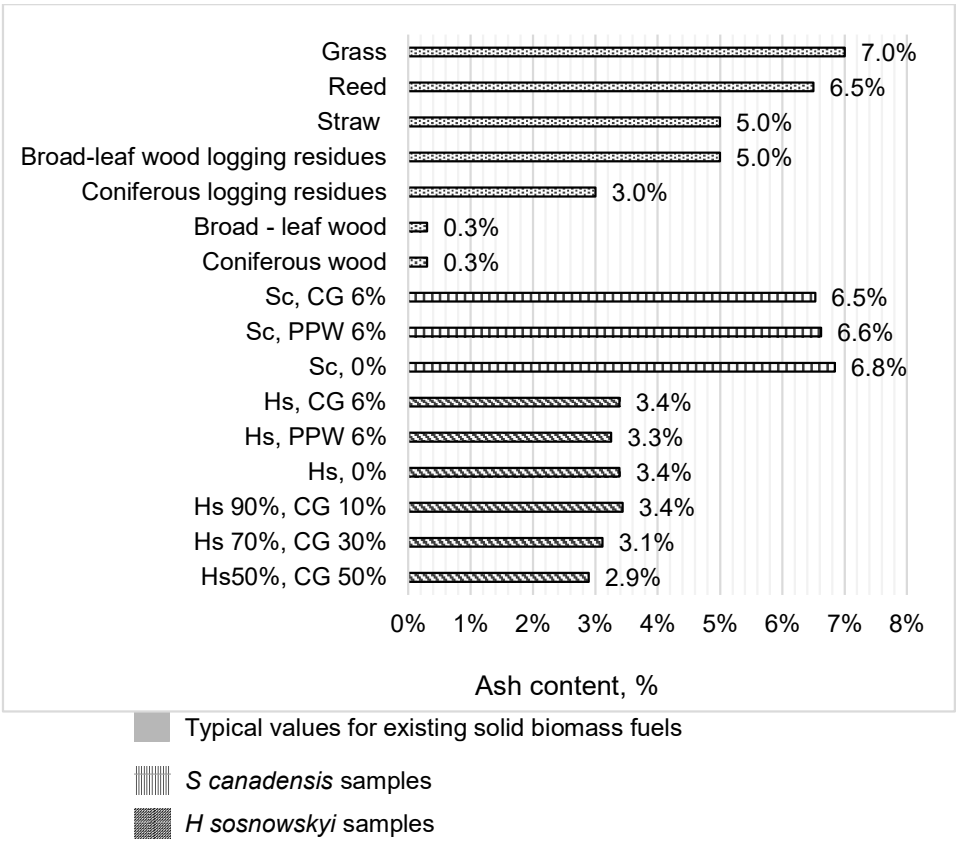

Figure 5. A comparison of ash content between existing solid biomass fuels and tested samples.

Fig. 5 shows the ash content values for existing solid biomass fuels and the tested samples. Typical values for existing solid biomass fuels are taken from the ISO 17225-1:2014 standard. The lowest ash content is for virgin wood material (broad-leaf and coniferous). Non-woody materials cannot compete with virgin wood materials. However, the average ash content for logging residues is between 3wt%-5wt%, which is similar to the ash content for *Heracleum*. The ash content of *Solidago* mixed samples

are similar to those for virgin reed canary grass, but the results for pure *Solidago* are similar to those for grass (in general).

CONCLUSIONS

The article's hypothesis has been partly verified. Invasive plant species, in terms of sustainability criteria for biomass selection, can be a suitable resource for the production of solid biofuel pellets, one which is easily replaced if the selected biomass is no longer available. But not all species show the best results. Not all binders can improve the quality of pellets in terms of biofuel parameters, but the coffee grounds as a binder have shown good results with *H sosnowskyi*, and there is a necessity to continue research with this binder and other raw materials where the ash content is high and the calorific value should be improved.

The methodology that has been created allows the appropriate raw materials and binders to be validated for solid biofuel production, a production which is low on cost and underused. The methodology helps to determine the quality of the resource and the properties of the added binder, so that the most effective species with the most effective binder can be selected, where they are also low on cost and widely available. As well as determining the optimum amount of binder that can be added, the parameters do not change or there is an increase in the calorific value and a decrease in the ash content.

The methodology can be improved by adding more biofuel-characteristic parameters into the selection and is effective in comparison with other solid biofuels.

The optimum coffee ground binder percentage is no more than 30% as the moisture content increases significantly. The increasing moisture content in higher proportions with coffee grounds could be reduced by means of oven drying.

Overall, the experimental analysis turned out better for *H sosnowskyi* pellets with a coffee ground binder. The calorific value and ash content can be competitive against wood. Therefore, it is possible to use this bioresource as an effective energy source. From those conclusions it can be seen that the use of *H sosnowskyi* with a coffee ground binder has been fully validated, and it is advisable to use this in industrial pellet production plants. However, from the energy balance and economics point of view, it is preferable to conduct further analysis. Further investigation for durability and bulk density for industrial pellets is clearly needed.

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