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CALORIFIC VALUE OF PELLETS FROM FRUIT DISTILLERY RESIDUES AS AN ALTERNATIVE TO AGRICULTURAL BIOMASS

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Abstract
The study evaluated the calorific value of pellets produced from fruit distillation residues and compared their energy potential with selected agricultural biomass. Residues of apricot, peach, and plum distillates were pelletized, conditioned to 10% moisture, and tested for gross calorific value using bomb calorimetry. Wheat and corn straw were analyzed as reference materials. A total of 30 replicates were measured for each pellet type, and statistical differences were assessed using one-way ANOVA. The results demonstrated that fruit-based pellets reached calorific values of 19.3–20.7 MJ/kg, while straw-based pellets achieved only 17.0–17.1 MJ/kg. In addition, ash content of fruit-based pellets was 42–75% lower compared to straw. Statistical analysis confirmed a highly significant effect of feedstock type ($P < 0.05$; F-value > F-crit; $\eta^2 > 0.99$). These findings highlight the energetic benefits of valorizing distillery residues and their potential as sustainable solid biofuels.

Key words: *calorific value; fruit distillation residues; pellets; agricultural residues; organic waste*

INTRODUCTION

Growing demands for the diversification of renewable energy sources and the reduction of emissions in the context of the circular economy are motivating the search for new uses of agricultural and food industry by-products. Among these residues are fruit distillation residues from fruit-based distilleries, which in the Central European region, including Slovakia, accumulate to tens of thousands of tons annually. Until now, their utilization has been largely limited to disposal in wastewater treatment plants, anaerobic digestion in biogas facilities, or occasionally as fertilizer, leaving their energy potential largely untapped. Biomass is one of the renewable and sustainable energy sources that does not lead greenhouse gas emissions. Efficient use of biomass energy will help to solve problems resulting from fossil fuels. However, the main concern relevant to use of this energy is mainly related to low calorific value of biomass. Therefore, calorific value is the key parameter to evaluate the fuel quality of a special biomass material in energetic applications *(Özyüğuran & Yaman, 2017)*. Compared to traditional fossil fuels, biomass has a number of beneficial characteristics that predispose it to wider use. It is a hydrocarbon fuel with a high oxygen content that has a zero carbon balance. This means that the carbon consumed in the energy generating process was generated entirely during relatively recent short period of time *(Mao, et. al., 2015)*. Plum stones have demonstrated considerable promise as an alternative biomass feedstock for the production of fuel and platform chemicals, with or without catalytic processes under various thermal conditions *(Pehlivan, 2023)*. Biofuels that achieve high combustion efficiency, particularly in gas turbines and boilers, are regarded as strong candidates for enhancing energy security while offering favorable environmental, economic, and societal benefits *(Bhoi, et al., 2020)*. Agricultural waste, in general, represents a viable source of renewable and clean energy. Residues from the cultivation of major crops constitute an attractive form of biomass suitable for the production of biofuels *(Akhmedov, et al.,2019)*. In recent years, the potential of non-traditional agricultural residues, especially fruit processing waste, has been highlighted as promising raw materials for the production of solid biofuels. If these materials are properly dried and processed into pellets, they can achieve calorific values comparable to, or even higher than, traditional biomass *(Agar, et al.,2018)*. The research on the energy properties of these residues not only supports sustainability goals but also facilitates technological innovations in rural bioeconomy models *(Ríos-Badrán, et al.,2020)*. An important advantage is that such pellets usually have a higher lignocellulose content, which improves their combustion and stability during combustion. In addition, their use in local bioenergy systems contributes not only to efficient waste management, but also to strengthening the energy self-sufficiency of regions *(Zawiślak, et al.,2020)*. Building on this background, the aim of the present study is to evaluate the calorific value of pellets produced from fruit distillation residues and to compare their energy potential with conventional agricultural biomass.

MATERIALS AND METHODS

The pellets from fruit distillation residues are prepared by separating the solid and liquid fractions using a FAN separator, model PSS 1.2 *(see Fig. 1A)*, which is installed at the distillery outlet of the distillation boilers. Its function is to isolate the solid phase suitable for further processing from the liquid phase, which is directed into a storage tank and subsequently treated in a biogas plant to balance pH levels. The separated solid fraction retains a residual moisture content ranging from 26% to 37%. For pelletizing the solid fraction of the fruit distillation residues, a STILER pellet press *(4 kW; see Fig. 1B)* was used.

A **B** **C**

Fig. 1 Separator FAN PSS 1.2 *(A)*; STILER pellet press *(B)*; Climate chamber HPP 110 *(C)*
Source: FAN Separator GmbH. (n.d.); MANTECH, s.r.o. (n.d.); UNIMED Praha, s.r.o. (n.d.)

The resulting pellets were subsequently conditioned to a uniform moisture content of 10% in a climate chamber HPP 110 *(see Fig. 1C)*, along with all other samples. The same pelletizing equipment was used for comminuted corn and wheat straw, and the subsequent procedures during measurement were identical.

After stabilizing the moisture content and weighing the samples to a mass of 1.00 g ± 0.05 g, the gross calorific value was determined. The lower heating value *(LHV)* was subsequently calculated using Equation *(1)*. A total of 30 samples were measured for each analyzed pellet type.

$$Q_i = Q_s - rH_2O \times (W + 8.937 \times x_H) \qquad (1)$$

where Q_s is the gross calorific value *(kJ.g^{-1})*, rH_2O the latent heat of water vaporization *(kJ.g^{-1})*, W is water content in the fuel, and x_H is the content of combustible hydrogen in the original sample *(mass fraction)*.

One-way analysis of variance *(ANOVA)* was used to evaluate the results, along with Cohen's effect size classification to assess the strength of the observed differences.

Methodological Procedure:

1. Data collection and organization
   Record the calorific values and ash mass measurements in the data collection form.
2. Calculation of statistical parameters
3. Comparison with the critical F-value or p-value

Based on the F-distribution and corresponding degrees of freedom, it is necessary to determine whether the calculated F-statistic is statistically significant.
If $F > F_{crit}$ or $p - value < \alpha$ $(e.g. 0.05)$, the null hypothesis H_0 is rejected, indicating a statistically significant difference between groups.

4. Application of Cohen's effect size classification
Cohen's effect size classification is used to quantitatively express the magnitude of the relationship or difference between groups, independently of statistical significance.
Eta squared (η^2)
$$\eta^2 = \frac{SSB}{ST}; - \quad (2)$$
Where SSB = sum of squares between groups; SST = total sum of squares *(SSB+SSW)*.
Cohen's f coefficient
$$f = \sqrt{\frac{\eta^2}{1-\eta^2}}; - \quad (3)$$
Cohen's effect size classification

RESULTS AND DISCUSSION

The energy recovery of agro-industrial waste is becoming an increasingly important component of waste management within the evolving circular economy. This study focused on analyzing the calorific value of pellets produced from conventional feedstocks such as wheat straw and corn straw, as well as from less common residues such as apricot, peach, and plum distillation waste. Based on laboratory measurements *(30 replicates per sample)*, average calorific values were determined for each type of pellet *(Fig. 2)* derived from fruit distillation residues and compared with those produced from agricultural biomass *(wheat and corn straw)*. The results are presented in Tab. 1. After recording the calorific value of each sample, the mass of the resulting ash was also measured and documented. The average percentage of ash content for each pellet type is reported in Tab. 1. To evaluate the measured calorific values—whose means and variability ranges are presented in Tab. 1, a one-way ANOVA *(Tab. 2)* was applied, accompanied by the calculation of effect size using Eta squared *(η^2)*. The results confirmed statistically significant differences among the evaluated feedstocks *($P < 0.05$; F-value = 6867.951 > F-crit = 2.434)*. The effect size reached $\eta^2 = 0.997$, which, according to Cohen's classification *(Tab. 2)*, represents a large effect far exceeding the threshold for a strong influence *($\eta^2 > 0.14$)*. This indicates that almost all of the variance in calorific value can be attributed to the type of material used for pellet production. These findings are consistent with previous research highlighting the energetic benefits of valorizing fruit processing residues compared to conventional agricultural biomass.

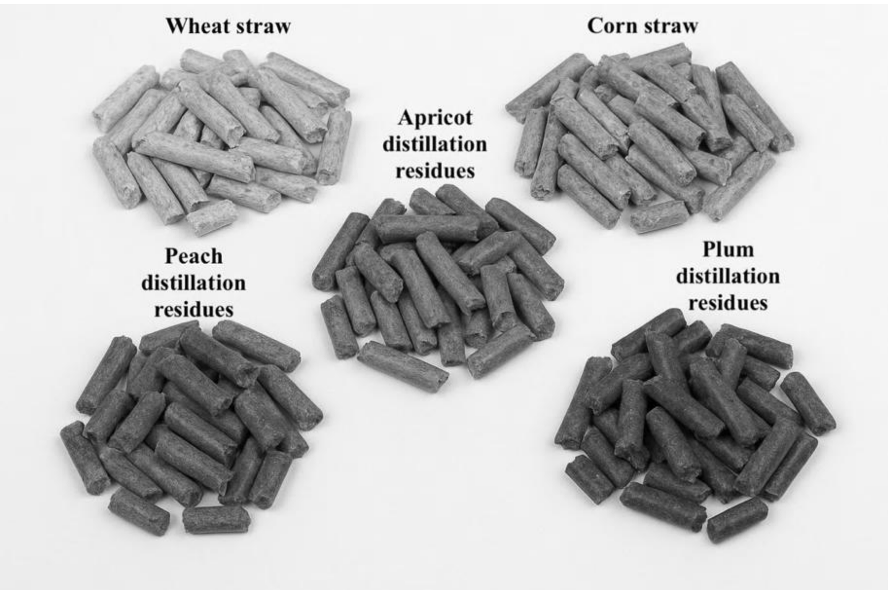

Fig. 1 Separator FAN PSS 1.2 *(A)*; STILER pellet press *(B)*; Climate chamber HPP 110 *(C)*

Tab. 1 Wire diameter range values for selected spring wire materials

Pellet Type	Average Calorific Value *(MJ.kg^{-1})*	Range *(MJ.kg^{-1})*	Ash Content *(%)*
Wheat straw	17.10	16.96 – 17.22	3.20%
Corn straw	17.04	16.91 – 17.22	3.99%
Apricot distillation residues	20.71	20.54 – 20.92	2.28%
Peach distillation residues	19.47	19.25 – 19.65	3.06%
Plum distillation residues	19.27	19.05 – 19.45	2.59%

Tab. 2 Anova – single factor analysis and Cohen's effect classification

Anova: Single Factor

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	308256449.1	4	77064112.28	6867.951	3.7856E-164	2.434
Within Groups	1627020.367	145	11220.83			
Total	309883469.5	149				
Cohen Eta squared *(η^2)*						
η^2	0.994749574					
η	**0.997**					

P < 0.05 or F-value > F-crit indicates significant difference.
SS: Sum of squares; df: Degrees of freedom; MS: Mean squares.

The data show a clear trend: pellets from fruit distillation residues demonstrated significantly higher calorific values and lower ash content compared to traditional agricultural biomass. Specifically, apricot-based pellets reached a peak calorific value of 20.71 MJ/kg, while peach and plum pellets also exceeded 19 MJ/kg. In contrast, wheat and corn straw pellets remained close to 17 MJ/kg. The ash content was also lower in the fruit residue samples, with apricot pellets generating only 2.28% ash compared to 3.99% in corn straw. Pellets produced from fruit distillation residues exhibited 12–15% higher calorific values compared to traditional agricultural residues *(wheat and corn straw)*, while the ash content was 42–75% lower in the fruit-residue-based pellets. Atimtay & Kaynak *(2008)* report a similar HHV value for peach stone *(20.65 MJ·kg−1 compared to our peach distillation residues 19.47 MJ·kg^{-1})* and a slightly smaller ash content of 1.5%. These findings are in line with previous research. Rzeźnik, Mielcarek & Rzeźnik *(2016)* observed that biomass pellets containing fruit processing waste achieved calorific values in the range of 19–20,5 MJ/kg depending on composition and moisture stabilization. Similarly, they found that stone fruit residues, especially dried and pelletized pits, can surpass 19 MJ/kg when properly densified. Pehlivan *(2023)* reported that the conversion of fruit waste via pyrolysis produced liquid fuels with high energy content, suggesting that even solid residues retain significant energy potential. Akhmedov et al. *(2019)* emphasized that pruning residues from fruit orchards such as apricot branches provide comparable calorific values to herbaceous biomass, supporting the viability of orchard waste. Moreover, the significantly lower ash content observed in this study aligns with the results of Rzeźnik, Mielcarek & Rzeźnik *(2016)* and Ordoudi, Bakirtz & Tsimidou *(2018)*, who demonstrated that fruit-based biomass generally contains fewer mineral impurities than cereal straws. This feature contributes to higher combustion efficiency and reduces the technical demands on ash management in pellet boilers.

CONCLUSIONS

The main results of the measurements indicate that pellets produced from fruit distillation residues *(apricot, peach, plum)* exhibit higher calorific values compared to those made from agricultural biomass *(wheat and corn straw)*. The average calorific value of fruit-based pellets ranged from 19.3 to 20.7 MJ/kg, with the highest value observed for apricot distillation residues *(20.71 MJ/kg)*. In comparison, the average calorific value of pellets made from wheat and corn straw was approximately 17.1 MJ/kg. Additionally, the ash content of fruit-based pellets was significantly lower, by 42–75%, than that of straw-based pellets, which can contribute to reduced maintenance requirements and improved combustion efficiency in biomass boilers. Statistical analysis using one-way ANOVA confirmed that the source material had a highly significant effect on the calorific value, with η^2 exceeding 0.99. These results emphasize the importance of feedstock selection in optimizing the performance of biofuel systems. These findings confirm that fruit distillation residues represent a more energy-efficient fuel source than conventional agricultural residues in terms of calorific output. Furthermore, ash disposal is often a challenge after combustion. In this context, pellets derived from fruit residues generated over 42% less ash compared to pellets from corn and wheat straw, significantly reducing the burden of post-combustion waste management.

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