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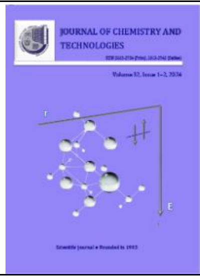


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## RESEARCH OF SOLID FUEL PRODUCTION FROM HORSE CHESTNUT SEEDS

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### Abstract

**The article presents the results of experimental studies using horse chestnut seeds (*Aesculus hippocastanum*) for the production of briquetted alternative solid fuel. Two types of crushed mixtures of horse chestnut seeds were used for the study: kernel and outer shell and kernel only. Calorimetric studies were carried out to determine the main parameters of the unformed and formed material: higher calorific value, ash content, and moisture content. It was determined that the average value of the higher calorific value for the unformed material is: for the mixture of the kernel and the outer shell of the seeds ~17549 kJ/kg, for the mixture of the kernel ~18351 kJ/kg. For the formed briquetted samples, the higher calorific value is ~18835 kJ/kg and ~18878 kJ/kg, respectively. The obtained data are close to the values of plant-based raw materials that are widely used to produce alternative solid fuels.**
*Keywords:* horse chestnut; *Aesculus hippocastanum*; alternative solid fuel; briquettes; biomass.

## ДОСЛІДЖЕННЯ ВИРОБНИЦТВА ТВЕРДОГО ПАЛИВА З ПЛОДІВ ГІРКОКАШТАНУ ЗВИЧАЙНОГО

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### Анотація

**У роботі подано результати експериментальних досліджень використання плодів гіркокаштану звичайного (*Aesculus hippocastanum*) для виготовлення брикетованого альтернативного твердого палива. Для досліджень було використано два види подрібнених сумішей плодів гіркокаштана звичайного: ядра та зовнішньої оболонки плоду та лише ядра. Проведено калориметричні дослідження визначення основних параметрів несформованого та сформованого матеріалу: вищої теплотворної здатності, зольності, залишкової вологості. Встановлено, що середнє значення вищої теплотворної здатності для несформованого матеріалу становить: для суміші ядра та зовнішньої оболонки плоду ~17549 кДж/кг, для для суміші ядра ~18351 кДж/кг. Для сформованих брикетованих взірців показники вищої теплотворної здатності становлять відповідно ~18835 кДж/кг та ~18878 кДж/кг. Одержані дані близькі до значень сировини рослинного походження, що широко використовується для одержання альтернативного твердого палива.**
*Ключові слова:* каштан; гіркокаштан звичайний; *Aesculus hippocastanum*; альтернативне тверде паливо; брикети; біомаса.

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## Introduction

The modern world is facing the need to find and implement new energy sources that would take into account environmental needs and reduce the impact of human activity on the environment. The significant dependence of society on traditional energy sources and the negative environmental impact associated with the use of coal, wood, and other traditional fuel resources encourage modern science and technology to actively develop alternative fuel sources.

Chestnuts are widespread throughout the world [1], and the seeds of these trees have practical uses. As of 2020, one of the largest chestnut producers in the world was China, where 1.965 million tons were grown, while global production was about 2.353 million tons [2]. Among the countries with significant chestnut production are Bolivia (84.01 thousand tons), Turkey (63.58 thousand tons), the Republic of Korea (53.384 thousand tons), and Italy (53.28 thousand tons) [2].

The structure of the chestnut is complex and functionally important for ensuring the viability of seeds. The seed consists of several layers, each of which performs its own function [3]. The outer shell has a protective role, helping to preserve the inner layers from damage and environmental influences. The inner chestnut peel, or endocarp, is a hard and tough structure that surrounds the inner core – its kernel. This layer protects the seed from mechanical damage and helps to hold the kernel. It can be divided into several segments. Each segment contains nutrients that make chestnuts valuable from a practical point of view [3].

Chestnut seeds have a rich composition of micro- and macronutrients, including cellulose, carbohydrates, proteins, fats, vitamins, and minerals [4; 5]. Certain types of chestnuts can be used as a food product in many countries around the world [6], both directly for eating and making flour [7] and flour products such as gluten-free cookies [7] and bread [8].

In pharmaceuticals, chestnuts find their place thanks to antioxidants and vitamins that support the immune system and the general condition of the body. They are used to alleviate inflammatory processes [3], are used to treat chronic venous insufficiency, and have a positive effect on venous tone, rheological properties, and blood clotting [3; 9]. Chestnut extracts are also used in skin care products [10].

One of such species is horse chestnut (*Aesculus hippocastanum*), which is a relative of traditional chestnuts and belongs to the *Sapindaceae* family. This plant has been used mainly in pharmacology, due to its chemical composition, namely the content of up to 28 % (by weight of dry seeds) of a mixture of toxic compounds – saponins [10]. At the same time, saponins are also widely used in the food industry for foaming [11; 12].

Taking into account the positive experience of using secondary raw materials of plant origin as a source for alternative solid fuels, such as alcohol distillery stillage [13], brewer's spent grain [14], and coffee production waste [15], it is of interest to study the seeds of horse chestnut for a similar purpose. Taking into account the structure and content of the seeds of horse chestnut, they have the potential to be used for energy needs; to be suitable for briquetting and pelletizing; to burn efficiently and without significant amounts of harmful emissions. The advantages of using this plant material also include its cheapness, availability, and low ability to adsorb urban emissions. In addition, the seeds of horse chestnut are a natural renewable resource that can be grown on a variety of soils, both separately and in combination with other woody plantations.

## Experimental part

For the production of solid fuel briquettes, it was used the seeds of the horse chestnut trees (*Aesculus hippocastanum*), shown in Fig. 1, which were gathered in a park area in Lviv, Ukraine.

Taking into account the structure of the horse chestnut seeds and the prospects for possible use, it was decided to prepare two types of experimental mixtures for briquetting. Experimental mixture №1 consisted of crushed kernels and the outer shell of horse chestnut seeds (Fig. 2, a), and experimental mixture №2 consisted of crushed kernels only (Fig. 2, b). For this purpose, the starting material was crushed in a laboratory electric mill and dried by the filtration drying method [16] to the moisture content required for storage and briquetting [17; 18], since wet material is not recommended for producing solid fuel briquettes [13].

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**Fig. 1. Seeds of the horse chestnut tree (*Aesculus hippocastanum*).**

To determine the average mass ratio in the mixture of the horse chestnut kernel and its outer shell, a series of experimental measurements were made. It was selected 20 freshly gathered seeds of horse chestnuts of different sizes, the kernels were separated from the outer green shell, and then it was determined the ratio of the kernel weight to the weight of each individual seed. Based on a series of experiments, the average ratio of the kernel weight to the weight of the whole horse chestnut seed was calculated, which was approximately ~42 % wt. The data was used to prepare the experimental mixture №1.

**Fig. 2. Dried experimental mixture №1 (a) and experimental mixture №2 (b) from the horse chestnut seeds used for the production of alternative solid fuel.**

Fuel briquettes were formed using a P474A hydraulic press. The pressing process parameters corresponded to the operating conditions given in [19]: pressure 9.81 MPa (100 kgf/cm$^2$), mold temperature 150 °C, pressing time 60 sec.

Calorimetric studies were conducted to determine the main characteristics of the formed and unformed material (higher calorific value, ash content, moisture content) in accordance with the requirements of the State Standards of Ukraine: DSTU EN 14918:2016 (EN 14918:2009, IDT). Solid biofuels. Method for determination of calorific value, DSTU ISO 18122:2017 Solid biofuels. Method for determination of ash content, DSTU EN 14774-2:2013. Solid biofuels. Determination of moisture content [13].

The methodology for conducting experimental studies of calorimetric combustion and a calorific value determination is described in detail in [13].

## Results and their discussion

The initial moisture content of experimental mixture №1 from the horse chestnut seeds was 45.93 % wt., and for experimental mixture №2 – 56.81 % wt. After drying the initial experimental mixtures by the filtration method, their moisture content was 6.83 % wt. (Fig. 2, a) and 7.43 % wt. (Fig. 2, b), respectively.

As part of the study, the initial experimental mixtures of raw materials and the obtained solid fuel samples were analyzed by the method of calorimetric combustion [13]. Considering the heterogeneity of the crushed biomass material, three parallel experiments were carried out and the parameter average value of the research object was determined.

Table 1 shows the average values of the higher calorific value of the dried experimental mixture №1 and experimental mixture №2.

*Table 1*

**Results of the experimental determination of the highest calorific value according to the calorimetry of combustion of experimental mixtures from the seeds of horse chestnut**

| Test, № | *m**, g | *ΔT*, V | $q_{ampoule}$, J | $q_{thread}$, J | $q_{HNO3}$, J | $q_{soot}$, J | *Q*, kJ/kg | *Q*, kcal/kg |
|---|---|---|---|---|---|---|---|---|
| Experimental mixture №1 | | | | | | | | |
| 1 | 0.25210 | 0.53851 | 1196 | 86.1 | 1.2 | 90.2 | 17372 | 4152 |
| 2 | 0.27107 | 0.56328 | 1057 | 107.2 | 0.6 | 78.7 | 17496 | 4182 |
| 3 | 0.16359 | 0.42180 | 1412 | 110.5 | 0.6 | 67.2 | 17780 | 4249 |
| | | | | | | *The average value:* | 17549 | 4194 |
| Experimental mixture №2 | | | | | | | | |
| 1 | 0.57556 | 1.11206 | 1057 | 64 | 3.5 | 108.2 | 18228 | 4357 |
| 2 | 0.33024 | 0.73027 | 1401 | 107.1 | 1.2 | 75.4 | 18539 | 4431 |
| 3 | 0.32322 | 0.70941 | 1417 | 100.8 | 1.8 | 88.6 | 18285 | 4370 |
| | | | | | | *The average value:* | 18351 | 4386 |

* *m* – the mass of the substance that burned during the experiment; $q_{thread}$, $q_{ampoule}$, $q_{HNO3}$, $q_{soot}$ – the amount of energy released during the combustion of cotton thread (16704.2 J/g), terylene ampoule (22944.2 J/g), the formation of a solution of nitric acid (59 J/g) and soot formed (32800 J/g), respectively; *ΔT* – true temperature rises in the calorimetric experiment [13].

In order to compare the average calorific value of the bulk mixtures of the study, Table 2 shows similar values for raw materials of plant origin, based on previous studies [13-15], and widespread plant materials from which solid fuels are produced on an industrial scale [20].

*Table 2*

**The higher calorific value of the study objects and their analogs**

| Raw materials of plant origin | Dried coffee production waste | Dried brewer's spent grain | Dried corn alcohol distillery stillage | Experimental mixture №2 | Energy willow | Experimental mixture №1 | Miscanthus |
|---|---|---|---|---|---|---|---|
| Calorific value, kJ/kg | ~ 21583 | ~ 20005 | ~ 19545 | ~ 18351 | ~ 17600 | ~ 17549 | ~ 17500 |

As can be seen from Table 2, in the unformed state, the average value of the higher calorific value of the experimental mixture №1 is almost at the level of the miscanthus and energy willow. At the same time, experimental mixture №2 has a slightly higher calorific value than its analogs but does not reach the level of secondary plant material produced by industrial food enterprises as a production waste. The data obtained show the prospects of research on the creation of alternative solid fuels from the seeds of horse chestnut.

The dried initial experimental mixtures of two types were pressed under the same process conditions to form briquetted experimental solid fuel mixtures. The parameters of the pressing process are given in the section “Experimental part”.

The obtained samples of briquetted experimental mixtures (Fig. 3) were similarly analyzed by the calorimetric combustion method, and the experimental data obtained are given in Table 3.

a

b

**Fig. 3. Solid fuel samples of briquetted experimental mixture №1 (a) and briquetted experimental mixture №2 (b) from the horse chestnut seeds.**

*Table 3*

**Results of experimental determination of the highest calorific value according to the calorimetry of combustion of briquetted experimental mixtures samples from the seeds of horse chestnut**

| Test, № | *m*, g | *ΔT*, V | $q_{ampoule}$, J | $q_{thread}$, J | $q_{HNO3}$, J | $q_{soot}$, J | *Q*, kJ/kg | *Q*, kcal/kg |
|---|---|---|---|---|---|---|---|---|
| Briquetted experimental mixture №1 | | | | | | | | |
| 1 | 0.82647 | 1.4816 | - | 87.8 | 8.9 | 300.1 | 18797 | 4493 |
| 2 | 0.97315 | 1.7484 | - | 75.6 | 4.1 | 321.4 | 18840 | 4503 |
| 3 | 0.75804 | 1.3763 | - | 96.0 | 7.7 | 165.6 | 18869 | 4510 |
| | | | | | | *The average value:* | 18835 | 4502 |
| Briquetted experimental mixture №2 | | | | | | | | |
| 1 | 0.74655 | 1.3593 | - | 89.4 | 3.0 | 132.8 | 18895 | 4516 |
| 2 | 0.92988 | 1.6863 | - | 60.8 | 14.8 | 172.2 | 18869 | 4510 |
| 3 | 0.86321 | 1.5647 | - | 79.3 | 9.4 | 185.3 | 18870 | 4510 |
| | | | | | | *The average value:* | 18878 | 4512 |

The obtained results of calorimetric combustion (Table 3) of briquetted experimental mixtures (Fig. 3) from horse chestnut seeds indicate an increase in the average value of the higher calorific value of solid fuel briquettes as a result of the material formation. For briquetted experimental mixture №1, this value increases slightly more than in comparison with briquetted experimental mixture №2, for the production of which the mixture of the kernel and its outer shell was used. The data are absolutely logical, given that the pressing process reduces the moisture content of the material and increases its density in the briquette. The average value of the higher calorific value in both cases exceeds that of widespread analogs, including miscanthus and energy willow, which makes the raw material of

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horse chestnut seeds promising for further research.

In addition, it was compared the average values of the higher calorific value of the briquetted experimental mixtures with these values for samples of alternative solid fuels from alcohol distillery stillage [13], brewer's spent grain [14], and coffee production waste [15], previously obtained under the same pressing conditions (Table 4).

*Table 4*

**The average value of the higher calorific value of briquetted experimental mixtures and their analogs**

| Raw materials of plant origin | Dried corn alcohol distillery stillage | Dried coffee production waste | Dried brewer's spent grain | Briquetted experimental mixture №2 | Briquetted experimental mixture №1 |
|---|---|---|---|---|---|
| Calorific value, kJ/kg | ~ 22445 | ~ 22147 | ~ 20173 | ~ 18878 | ~ 18835 |

The ash content of the experimental mixtures and briquetted experimental mixtures are given in Table 5 based on the results of the calorimetry of combustion. We note the increase in the values for briquette mixture №1, which may be due to the residues of sand or soil on the shell of the horse chestnut seed in the biomass used for the mixture creation. The residual moisture content of all experimental mixtures is less than 1 % wt.

It is also worth noting that during pressing at elevated pressure and temperature, vapor with a specific odor was observed, which affected those present in the laboratory with a slight headache. Taking into account the chemical composition of horse chestnut seeds, such substances are likely to be products of the thermal decomposition of saponins [10], which might be harmful to humans. The process of gas formation during the briquetting and combustion, the composition of the gases formed, and their impact on the human body require additional research and analysis.

*Table 5*

**Average values of ash content of experimental mixtures and briquetted experimental mixtures of horse chestnut seeds**

| Experimental samples of the horse chestnut seeds | Ash content, % wt. |
|---|---|
| Experimental mixture №1 | ~ 1.3 |
| Experimental mixture №2 | ~ 1.6 |
| Briquetted experimental mixture №1 | ~ 4.1 |
| Briquetted experimental mixture №2 | ~ 2.1 |

Taking into account the experimental data obtained, the seeds of the horse chestnut theoretically may be used for producing alternative solid fuels with the calorific values of the existing standards [21]. The experimental data obtained are close to the Swedish standard SS 187120, according to which the main characteristics of biofuels are within the following limits of calorific value (>16910 kJ/kg), ash content (<1.5%), residual moisture (<10%) [22], as well as to the German standard DIN 51731: calorific value (15512÷19515 kJ/kg), ash content (< 1.5 %), residual moisture (< 12 %), but there is an excess of ash content in the briquetted experimental mixtures. One of the possible ways to solve the problem of high ash content may be the creation of combined alternative solid fuels with the addition of other high-energy raw materials of plant origin to the crushed horse chestnut seeds.

## Conclusions

As a result of the research, briquetted samples of alternative solid fuels from the horse chestnut seeds were obtained. The main parameters of both the unformed experimental mixtures and their briquetted samples were researched. The average value of the highest calorific value was experimentally determined, which for the unformed experimental mixture №1 is ~17549 kJ/kg, and for the dried experimental mixture №2 is ~18351 kJ/kg.

The solid fuel was formed by pressing the experimental mixtures on the hydraulic press. The resulting briquetted experimental mixtures were analyzed by the calorimetric method and the main parameters of the obtained briquettes were determined. An increase in the average value of the higher calorific value was observed, which for briquetted experimental mixture №1 is ~18835 kJ/kg, and for briquetted experimental mixture №2 is ~18878 kJ/kg.

Thus, the possibility of using of the horse chestnut seeds for the production of solid fuels has been shown. The average value of the higher calorific value for the briquetted experimental mixtures of the conducted studies is higher than in widely used plant analogs, including miscanthus and energy willow, which makes the selected plant material promising for further research.

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