International Journal of Heat and Technology
Vol. 42, No. 3, June, 2024, pp. 749-754
Journal homepage: http://iieta.org/journals/ijht

Economic and Ecological Aspects of Combustion of Selected Types of Biomass in Low-Power Heating Boilers

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https://doi.org/10.18280/ijht.420304

Received: 26 February 2024
Revised: 4 April 2024
Accepted: 12 April 2024
Available online: 27 June 2024

Keywords:
biomass, pellets, combustion, domestic boiler

ABSTRACT

The article presents an analysis of the suitability of four kinds of pellets produced from different types of biomass as heating fuel. One type of wood biomass (pine wood), two types of waste biomass from the food industry (sunflower husk and rapeseed cake) as well as one sort of biomass crop for energy purposes (willow) were chosen. Following proper preparation, the chosen biomass materials underwent the process of pelletization and their selected physicochemical properties were determined. While burning pellets in a domestic heating boiler, the composition of exhaust gases was analyzed. It was observed that rapeseed cake pellets do not fulfil the standards regarding calorific value, ash and nitrogen contents, therefore it is not possible to burn them in low-power boilers. It has been shown that the pellets from pine, sunflower and willow generally meet the quality standards, however, when analyzing the costs of generating 1 GJ of heat, the willow pellets seem to be the best fuel.

1. INTRODUCTION

For the sake of human well-being and world economic growth, in the past few decades there has been rapid consumption of natural resources, along with higher CO_2 emissions, leading to greater attention to ecological issues [1].

This situation is mainly owing to the fact that the energy sector in the majority of European countries is fossil fuel-based. The combustion of such fuels as crude oil, coal and natural gas creates considerable emissions of pollutants, which, as a consequence of progressively higher environmental standards, require a constant reduction of those emissions [2, 3].

The European Commission has defined the energy strategy included in the Framework for Climate and Energy document, which sets out the goals and scenarios to be achieved by 2030. According to the above-mentioned document, the share of renewable energy sources must be increased to at least 27%, and emissions greenhouse gases (GHG) reduced by up to 40%. This solution aims to improve energy efficiency and provide competitive, safe and affordable energy [4]. Moreover, in the context of the ongoing war in Ukraine, this issue has become even more important due to the dependence of many European Union (EU) member states on supplies of Russian gas and coal. Therefore, the use of renewable energy provides many ecological and economic benefits, such as diversification of energy suppliers, independence from fossil fuels and lower greenhouse gas emissions [5].

A variety of renewable and alternative energy sources that can be utilized in place of conventional and fossil fuels exist. These include solar, wind, hydro, ocean, geothermal, as well as biomass and biofuel energy [6]. Biomass is widely used in the world and is the most common renewable energy source. Depending on climatic conditions, it can be obtained from various organic wastes (e.g. rapeseed cake, soybean husks, rice, cotton or sunflower husks, nut shells, olive or plum pits), harvest residues (e.g. straw from corn, oats, wheat, rapeseed or rice) and wood biomass (e.g. wood, sawdust or bark from pine, spruce, oak, or poplar) [7, 8]. One of the several benefits of using biomass for energy is the possibility to reduce greenhouse gas emissions, i.e. carbon dioxide, as well as the toxic components of combustion gas - carbon monoxide, sulfur dioxide, chlorine compounds and nitrogen oxides [9-12].

The fact that biomass is produced in the process of photosynthesis, where under the impact of solar radiation carbohydrates are obtained from CO_2 and H_2O, is its major advantage. Thus, the amount of CO_2 needed to grow biomass equals the emissions of that gas during combustion, and therefore results in zero carbon dioxide emissions when burning biomass. It has been estimated that in comparison to coal, during the combustion process of biomass the amount of generated greenhouse gases is more than 90% less [13-15]

The harmful effects of GHG have been known for a long time, as presented in many scientific articles [16-19]. According to Pearce and Parncutt [18], if the average global temperature increases by 2℃ in the 21st century, it may contribute to the death of up to a billion people, mainly living in poorer countries. Richer countries that do not follow the principles of sustainable development will be responsible for this state of affairs

That is why sustainable energy management is so by reducing the consumption of fossil fuels important at the expense of renewable energy sources, especially in richer countries. Hence, using biomass for the purposes of heating (e.g. in pellet form) seems to be an alternative that is a easy, inexpensive and environmentally friendly. Thus, boiler installations fueled by biomass pellets have become an environmentally friendly and ever more popular heating method in recent years. Biomass boilers are progressively becoming more modern, they are automated and provide acceptable combustion efficiency [20-22]. Wood from wood industry products is the main source of biomass for pellet production, resulting in greater costs of obtaining this kind of pellets in Poland. The imposed value added tax (VAT) rate of 23% on wood fuels is the reason for these high costs. In comparison, pellets from waste biomass carry an 8% VAT while for energy crops it is 7%. Hence, it seems to be more economical to produce pellets from other raw materials than wood [23, 24].

Willow (*Salix viminalis*) has the greatest potential among energy crops in Europe since it does not require large amounts of work, does not have high soil requirements, and is characterized by low energy consumption, as well as high productivity [25-27]. It is also worth considering selected waste from the food industry, which could be a cheap and widely available source for the production of pellets [28, 29]. Waste generated, for example, from the production of vegetable oils for food or energy purposes, may be high in calories [30, 31]. Good examples are sunflower husk and rapeseed cake. Rapeseed is the most common crop cultivated for the production of oil in the EU, whose the share in the total area of oilseed crops is over 80%, whereas sunflower is one of the world's leading oil seed crops [8, 32, 33].

The raw materials mentioned above can serve as alternatives to wood for the production of pellets [11, 24, 34]. Nevertheless, the physicochemical properties and chemical composition may differ from the standards, therefore having a negative impact on the exhaust gas composition as well as on the operation of boilers and their maintenance [35-38].

Therefore, the main aim of the research presented in the article was to analyze selected physicochemical properties as well as the combustion process for four types of fuels produced from wood and waste. Raw materials for pellet production were selected based on availability on the Polish market and divided according to the type of biomass.

One type of biomass grown for energy purposes (willow), two kinds of waste biomass (rapeseed cake, sunflower husks,) and one type of wood (pine) were chosen. Following proper preparation, the chosen starting materials underwent the process of pelletization. The produced pellets were tested for moisture content, ash, calorific value and elemental composition. Their dimensions, bulk density as well as the cost of producing 1 GJ of heat were also determined. A domestic heating boiler designated for burning pellets was employed to burn the produced fuels. An exhaust gas analyzer was utilized to ascertain the concentrations of CO_2, CO, and NO_x.

2. METHODOLOGY

One type of wood biomass was selected for analysis - pine sawdust, two types of waste biomass from the production of vegetable oil - rapeseed cake and sunflower husk, and one type of energy biomass - willow *Salix viminalis*. Materials for research were obtained from the Polish Refinery in Trzebinia and the farm of L.K. in Radomsko Following proper preparation (cleaning, drying, and grinding), the investigated raw materials underwent the process of pelletization using a ZLSP 150B pellet mill with a power of 4 kW and a rotational speed of 250 rpm from Anyang Gemco Energy Machinery. The pellet machine was equipped with a die with a hole diameter of 6 mm. Pellets were produced at an average speed of 20 kg/h. The process used calcium lignosulfonate in the form of a binder in an amount of approximately 2% and water. Figure 1 presents the preparation process of the chosen kinds of biomass for heating fuel.

Figure 1. Schematic diagram of preparation of selected types of biomass for heating fuel, where: 1 - pine, 2 - sunflower husk, 3 - rapeseed cake, 4 - willow (Salix viminalis)

Samples of the researched pellets underwent grinding in a knife mill with a sieve diameter of up to 1 mm so as to ascertain the elemental composition and selected physicochemical properties. The weight loss of a 1.00 g sample following drying at 105 ± 5°C to a constant weight was the method to determine the moisture content, in accordance with the EN ISO 18134-3:2015 standard. A 1 g sample of all the investigated pellets were burned in a muffle furnace at 250 ± 10°C for 50 minutes, afterwards at 550 ± 10°C for 4 hours so as to determine the ash content, according to the EN ISO 18122:2015 standard. The net calorific values (NCV) of the studied pellets were ascertained by means of a KL-12Mn PRECYZJA-BIT calorimeter, in accordance with the EN 14918:2009 standard. According to the EN ISO 17828:2016-02 standard, the bulk density of the produced pellets was determined.

The contents of hydrogen [H], carbon [C], and nitrogen [N] were ascertained utilizing a LECO Truspec CHN628 elemental analyzer. The device measures C, H, N using two types of detectors: Thermal conductivity and infrared absorption. The diameter and length and of the produced pellets were also measured. The received results were compared with the PN-EN ISO 17225-2: 2014 standard.

The pellets were burned in a Mini Bio 10 kW domestic biomass boiler Kostrzewa (Poland). The main element of the boiler is the Platinium Bio burner, which can burn pellets with a diameter of 6 to 8 mm. The composition of exhaust gases emitted from the boiler was constantly examined using the Vario-Plus analyzer, equipped with infrared sensors for the analysis of CO, NO_x and CO_2. Figure 2 illustrates the test stand.

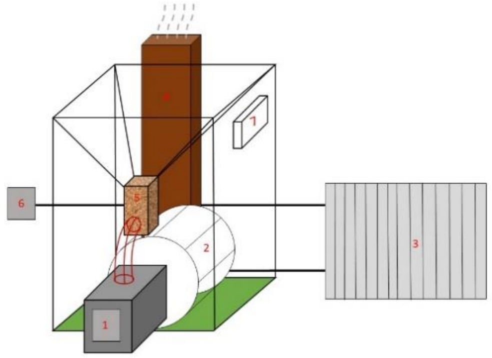

Figure 2. Experimental station for burning pellets, where: 1 - burner, 2 - combustion chamber, 3 - heat receiver, 4 - exhaust gas removal, 5 - feeder, 6 - analyzer, 7 - controller

3. RESULTS AND DISCUSSION

The physicochemical properties of the produced pellets from the selected raw materials are presented in Figures 3 and 4.

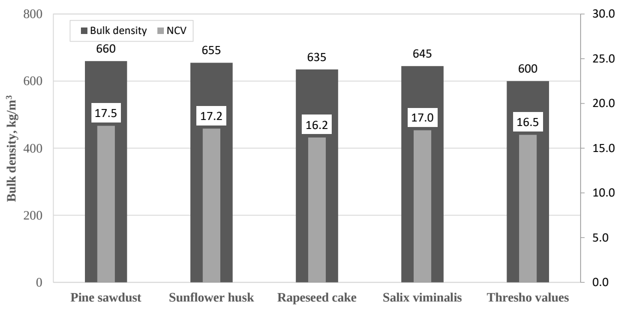

Figure 3. Comparison of bulk density and net calorific value with the PN-EN-ISO-17225-2:2014 standard for the analyzed pellets

Figure 4. Comparison of moisture and ash content with the PN-EN-ISO-17225-2:2014 standard for the analyzed pellets

As shown in Figure 3, pine pellets have the highest NCV value (17.5 MJ/m^3), and rapeseed cake pellets have the lowest (16.2 MJ/m^3). Sunflower husk and Salix willow pellets have a similar NCV value (17.1 ± 0.1 MJ/m^3).

Pine sawdust pellets also have the highest bulk density (Figure 4), and they are also characterized by the lowest moisture and ash content in comparison to other analyzed pellets. The most of the ash is generated during the combustion of rapeseed cake pellets. Analyzing the obtained results, it can be seen that only oilseed rape pellets do not meet the PN-EN ISO 17225-2:2014 standard regarding the net calorific value or ash content. The elemental analysis of the researched biomass fuels is shown in Figure 5.

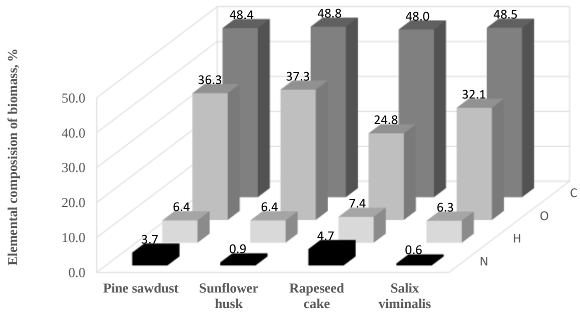

Figure 5. Elemental composition of biomass pellets

The requirements are not specified in the standard regarding the hydrogen carbon contents in pellets. There are, however, requirements regarding the content of chlorine, nitrogen, and sulfur, the nitrogen content should not exceed 1% in accordance with the standard. As shown in Figure 5, a clear deviation from the norm can be observed for rapeseed cake and pine pellets. This is most likely due to the high protein content in this raw material, which ranges from 31 to 34%. Based on the literature review [8, 39], it was observed that the contents of sulfur and chlorine and in the studied raw materials used to produce the pellets do not exceed 0.1%; therefore, it was assumed that in terms of the content of these elements, the investigated pellets also comply with the EN-ISO-17225-2: 2014 standard.

Figure 6 displays the concentrations of CO_2 NO_x, and CO in the flue gas of the analyzed pellets.

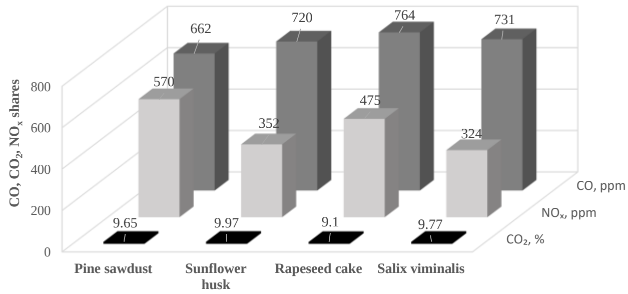

Figure 6. Average concentrations of CO_2 NO_x, and CO in flue gas from burning of studied pellets

The highest NO_x concentration was seen during the combustion of the pine and rapeseed cake pellets, probably resulting from a higher share of nitrogen compared to the pellets made from the sunflower husk and willow. The highest concentration of CO and lowest concentration of CO_2 were observed when burning the rapeseed cake pellets, which may be the result of their incomplete combustion. In turn, the highest CO_2 concentrations were generated through the sunflower husk pellets burning, resulting from the fact that this type of pellets has the highest carbon content. The costs of generating 1 GJ of heat (CGH) were determined, taking into account the price of the produced fuel (P_F), the net calorific value (NCV) and the boiler efficiency (η) required for domestic 5th class heating boilers adapted to burning pellets, based on the formula:

$$\mathrm{CGH} = \frac{\mathrm{P_F}}{\eta \cdot \mathrm{NCV}}, \mathrm{zl/GJ} \quad (1)$$

Figure 7 shows the average prices of raw materials available on the Polish market, from which the pellets were produced. The prices of the produced pellets are also presented; the price includes 7%, 8% and 23% VAT, which is dependent on the raw material. The same cost of pellet production was assumed, regardless of the raw material.

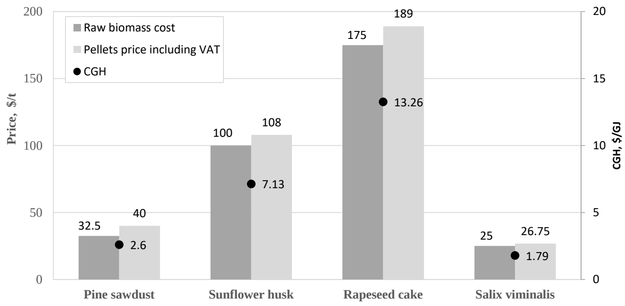

Figure 7. Analysis of profitability of using produced pellets for heating purposes

The fuels that generate the highest costs of producing 1 GJ of heat are the pellets from rapeseed cake and sunflower husk. This is due to the high price of those raw materials, which, owing to their properties, can also be used as animal feed. Therefore, despite the high calorific value of these pellets, burning them is not profitable. The least expensive fuels occur be the pine and willow sawdust pellets, and taking into account the appropriate elemental composition and physicochemical properties, pellets produced from these raw materials may be an economic and ecological alternative to fossil fuels.

4. CONCLUSIONS

In times of the limited availability and rising prices of fossil fuels, it is highly important to seek new, less expensive solutions, especially in the area of fuels produced from commonly available biomass, which includes waste biomass. Nonetheless, some of these types of fuels do not meet the standards concerning the appropriate ash content or calorific value. It is extremely important to find alternatives to fossil fuels both in terms of economics and ecology. Therefore, the study analyzed four types of biomass pellets widely available on the Polish market. One type of wood biomass (pine sawdust), one type of energy biomass (willow) and two types of waste biomass (sunflower husk and rapeseed cake) were analyzed. The conclusions that were drawn from the research conducted in this article are as follows:

- Pellets made from pine, sunflower and willow husks comply with the EN-ISO-17225-2:2014 standard in terms of net calorific value (≥17 MJ/kg), dimensions (diameter 6 mm, length 5-30 mm), ash (≤2%), moisture content (≤ 6%) and bulk density (≥645 kg/m^3).
- Pellets from rapeseed cake cannot be used as fuel for heating purposes as a consequence of to their almost three times higher ash content (5.8%), too low calorific value (16.2 MJ/kg) and the more than twofold nitrogen content (4.7%) compared to the other pellets in the study. When burning them in a home heating boiler, the CO concentration was high (764 ppm), which was most likely owing to their incomplete combustion. Moreover, these wastes have a high protein content and are commonly utilized as a feed additive, which is why their price is high, thus resulting in high costs of generating 1 GJ of heat.
- Sunflower husk pellets meet the standards for all the analyzed parameters, however, as in the case of rapeseed cake, they can be used as a feed additive; therefore, their combustion is financially unprofitable in Polish conditions.
- The best fuels in terms of price and calorific value are the willow and pine pellets. However, the analyzed pine pellets are characterized by too high nitrogen content (3.7%), which causes the emission of high concentrations of nitrogen oxides (570 ppm) during their combustion. The best and least costly fuel seems to be the energy willow pellets. The wide availability of the raw material resulting from its low soil requirements and rapid weight gain over time makes it a fuel with a high potential for use, both in the energy sector and in low-power home boilers.

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