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# Jerusalem Artichoke as a Raw Material for Manufacturing Alternative Fuels for Gasoline Internal Combustion Engines

**Michał Bembenek [1,*], Vasyl Melnyk [2], Bolesław Karwat [1], Mariia Hnyp [2], Łukasz Kowalski [1] and Yurii Mosora [2]**

[1] Faculty of Mechanical Engineering and Robotics, AGH University of Krakow, A. Mickiewicza 30, 30-059 Krakow, Poland; karwat@agh.edu.pl (B.K.); lkowalski@agh.edu.pl (Ł.K.)
[2] Institute of Mechanical Engineering, Ivano-Frankivsk National Technical University of Oil and Gas, 76019 Ivano-Frankivsk, Ukraine; vasyl.melnyk@nung.edu.ua (V.M.); mariia_hnyp@ukr.net (M.H.); yuramosora@gmail.com (Y.M.)
* Correspondence: bembenek@agh.edu.pl

**Abstract:** The Jerusalem artichoke (*Helianthus tuberosus*) is a high-yield crop, and a great source of fermentable sugars, which gives the plant the potential to be used as raw material for economical fuel alcohol production. In this article, the authors focus on the technological aspect of the biofuel manufacturing process and its properties. First, the fuel alcohol manufacturing process is described, afterwards assessing its characteristics such as kinematic viscosity, density and octane number. The amount of fuel alcohol obtained from 10 kg of biomass equals to 0.85 L. Afterwards, the mixtures of gasoline and obtained fuel alcohol are prepared and studied. Optimal alcohol and gasoline mixtures are determined to obtain biofuels with octane ratings of 92, 95 and 98. The kinematic viscosity of obtained mixtures does not differ significantly from its values for pure gasoline. The obtained biofuel mixture with 25% alcohol content yielded a decrease of sulfur content by 38%, an increase of vaporized fuel amount by 17.5% at 70 °C and by 10.5% at a temperature of 100 °C, which improves engine startup time and ensures its stable operation in comparison to pure gasoline. The alcohol obtained can be successfully used as a high-octane additive for gasolines.

**Keywords:** biofuel; bioethanol; green energy; internal combustion; biomass conversion

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## 1. Introduction

Due to the growing requirements for the quality and environmental friendliness of engine fuels and fossil energy reserves, the issue of their full or partial replacement with alternative and renewable energy sources is widely discussed in the literature. Ensuring the quality of fuel also impacts the longevity of consumer vehicles' engines [1]. Alcohols and their compounds are one of the alternatives for fuel used in internal combustion engines [2]. The largest cost in manufacturing biofuels is the cost of the biomass source, so its proper selection is crucial. Scientists in [3–7] have studied the cultivation and possibilities of yield increase of the Jerusalem artichoke.

It is possible to find varieties of *Helianthus tuberosus* that allow to obtain higher yields of tuber and aboveground mass, as well as increase the biomass' energetic properties [3]. In [4], researchers pointed out important directions for related research:

- Optimization of cultivation conditions to increase crop yields per input,
- Increasing the inulin content in tubers by genetic modification of the species,
- Identification and development of enzymes with high activity and stability to increase manufacturing efficiency.

The biofuel ethanol might be manufactured out of many cellulose- or sugar-yielding crops, such as sugarcane, corn, switchgrass, potatoes, etc. [8]. Residues from non-forage crops might also be used as a source material for biofuel alcohol production [9]. The plant, native to the North America region, can provide high biomass yield and can be cultivated in many regions, f. ex., China [10] or diverse and marginal agricultural areas in Europe [11], thus signifying the plant's potential as a sustainable and cheap source of renewable biomass.

In [5], the authors suggest that large-scale research to improve the fermentation process using various approaches (such as optimization of fermentation parameters and advanced bioreactor designs) should be conducted. Gunnarsson et al. [6] assessed the potential of Jerusalem artichoke as a feedstock for bioethanol, protein and inulin production. They studied the biomass efficiency and chemical composition of 11 different samples collected three times during the fall and early winter of 2011, showing that harvest time is an important factor affecting biomass productivity and composition, but no studies were conducted on the quality and volume of alcohol yield. Research by Kowalczyk-Juśko et al. [7] highlighted that aboveground parts of Jerusalem artichoke obtained after drying are characterized by unique energy parameters in comparison to other sources of biomass. The beforementioned authors also found the drawbacks of *Helianthus tuberosus* as an energy source, specifically the chemical composition of its ash and its low melting point. These features indicate the risk of carbon deposits forming on heat exchangers, which can reduce the efficiency of boilers.

The importance of renewable energy sources in the energy balance of Europe has been studied by scientists in [3,12,13]. In [3], researchers estimated the calorific and energy values of Jerusalem artichoke biomass and assessed its potential for bioethanol and biogas production, but the manufacturing process and the quality of the ethanol produced were not studied. In [12,13], authors present different methods of producing biodiesel from JA tubers—by cultivating microalgae. The researchers studied the oil manufacturing process from microalgae but did not investigate bioethanol production. The issue of using dry plant biomass as a source for the production of biofuels and biochemicals in the process of hydrocarbon replacement is discussed in [14–40]. It has been established that biomass pretreatment promotes enzymatic hydrolysis and increases glucose yield from cellulose by removing hemicellulose or lignin [14,15]. However, the main disadvantage of lignocellulose biorefining is its high cost. Thus far, various methods of biomass pretreatment have been developed; for example, using alkali, dilute acid, hot water, steam or ionic liquids [16]. Among these methods, alkaline pretreatment is the most effective for removing lignin and improving cellulose content [17–19], which increases alcohol yield from the resultant preproduct. Pretreatment with sodium hydroxide can remove 10.9 g of lignin from rice straw, preserving 91.54% of cellulose and preserving the hemicellulose, but the high cost and difficulty of the process, as well as the pollution caused by wastewater discharge, hinders its industrial application [20,21].

Results presented in [22,23] describe the possibility of reutilization of black lye solution at least five times for straw pretreatment and lignin extraction using acid precipitation [24,25]. The main purpose of acid pretreatment is to dissolve the hemicellulosic fraction of biomass and make cellulose more accessible to enzymes [26], which demonstrates the excellent degradation capability of lignocellulosic-derived inhibitors [27]. Some studies focused on combined acid/alkali pretreatment processes with 82% cellulose, less than 1% hemicellulose and 30% lignin being obtained from hollow palm fruit fibers [28]. Combined pretreatment of JA stems with $HNO_3$ and NaOH allows for reaching glucose conversion at 90.6% of the maximum theoretical value [29]; however, the high waste generation of such a process resulted in research on the possibility of reusing the pretreatment solution [23,30,31].

The main advantages of JA are, among others, its ability to grow in poor soil, resistance to pests and common plant diseases and growing much better (in comparison to other energy crops) under salt stress and low temperatures [32,33]. JA tubers are an excellent source of biomass for biofuels and biochemicals manufacturing and have been investigated for ethanol fermentation [34–41], but the use of JA stems as a lignocellulosic feedstock for biofuels and biochemicals is still poorly understood [42]. Further, scientists refer to JA as an energy crop that is profitable to burn, easy and cheap to cultivate [43–45]. Biomass, and in particular energy crops, grows quickly and is considered renewable in comparison to fossil fuels.

After the state-of-the-art review, the authors observed that most studies aim at increasing the yield of JA to obtain more biomass for the production of fuel alcohol and bioethanol from cellulose by hydrolysis. Therefore, the issue of researching the technological process of bioethanol production by alcoholic fermentation is relevant and promising since, according to preliminary studies, the alcohol yield from 1 ton of JA tubers is 2–2.5 times higher in comparison to the yield from stems and 1.5–3.4 times higher than the alcohol yield from processing other crops, such as sugar beet, potatoes or wheat (per unit area of planting).

## 2. Materials and Methods

This work aims to study the technological process of bioethanol production from JA by alcoholic fermentation and to evaluate the main technical and operational parameters of the resulting biofuel. The detailed objectives are:

- To improve the methodology of alcoholic fermentation of JA biomass.
- To manufacture the fuel alcohol.
- To study the physicochemical and operational characteristics of the obtained fuel alcohol combined with commercial gasoline.

In this study, authors used JA tubers grown on their own experimental plot. The plants were planted with the distance between the rows equal to 70 cm and between the plants in a row equal to 60 cm. Some of the crop obtained is presented in Figure 1.

**Figure 1.** Crop obtained from the experimental plot.

The tubers were chopped using a chopper manufactured by LLC "Pivden-Service" (Kyiv, Ukraine) instead of being pressure-boiled as literature usually recommends. The maximum size of obtained tuber chips was 20 mm long and 8 mm in diameter. Afterwards, the crushed mass was acidified with sulfuric acid to pH = 2. For saccharification, the mixture was heated with periodic stirring to 92–96 °C and kept under these conditions until the end of the process. The process was completed when the whole mass turned to a light brown color and had a fruity odor and sweet taste. After the pulp cooled down to 23–24 °C, bread yeast diluted with warm water was mixed in.

The fermentation process was carried out without stirring for the first 12–16 h, and with periodic stirring for the next 12–16 h, at a maintained temperature of 26–30 °C.

The alcohol was then distilled from the fermented mass in 2 stages: by direct distillation and then rectification on a column. The rectification was carried out on a 1000 pilot column filled with Raschig rings, with the column's diameter D = 150 mm (Figure 2).

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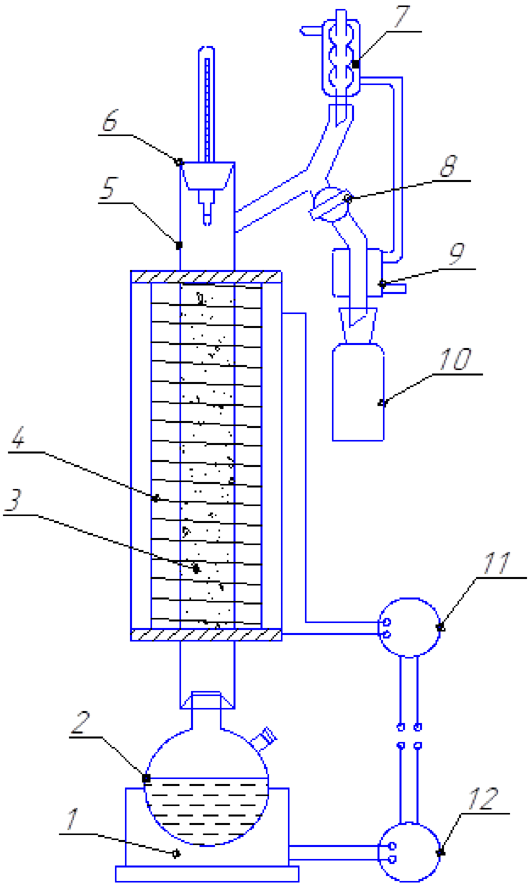

**Figure 2.** Diagram of the distillation unit. 1—flask heater; 2—the flask; 3—Raschig rings; 4—electric spiral; 5—column; 6—thermometer; 7—deflagrator; 8—tap; 9—condenser; 10—collection vessel; 11, 12—laboratory autotransformer.

The experimental setup presented in Figure 2 consists of a flask (2) connected to an electrically heated (4) column (5) filled with Raschig rings (3). The thermometer (6) is placed in the column's seal. The distillation column is equipped with deflagrator (7), condenser (9) and collection vessel (10). The temperature of the flask and the column was controlled and regulated by laboratory autotransformers (11,12).

As a result of rectification, 3 fractions were obtained: the main fraction containing 92–93% alcohol vol. and secondary fractions with 60–63 and 45–50% alcohol vol. The total amount of alcohol obtained from 10 kg of tubers was 0.85 L.

Subsequently, the main physical and chemical parameters of the obtained fuel alcohol were assessed. The octane number of the alcohol was measured with a SHATOX SX-100K device (LLC Ukrpribor, Kyiv, Ukraine) in accordance to its operating manual. The fractional composition of the alcohol was determined using an Engler device (LLC Khimtest Ukraine+, Kharkiv, Ukraine) with a maximum measurement error of ±2%. The fractional composition test was performed at an ambient temperature of 20 °C and barometric pressure equal to 735 mmHg.

The fractional composition was examined by determining the temperatures at the beginning and end of fuel boiling, and the content of fractions at set temperatures. Before the test, the examined fuel was thoroughly dehydrated using calcium chloride. For the experiment, 100 mL of dehydrated fuel was poured into the flask, ensuring that none of the liquid stuck to the flask's outlet. The flask was then placed on a heat-insulating pad. The flask's neck was then inserted into the cooling tube and sealed with a cork. All connectors of the setup were then carefully sealed with an adhesive.

The cylinder used for measuring the fuel, without drying, was placed under the lower bent end of the cooling tube in a way that the tube entered the cylinder by at least 25 mm

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and did not touch the walls of the cylinder. During distillation, the cylinder was covered with cotton wool to prevent vapor loss. After preparing the apparatus for distillation, the barometric pressure was recorded. If it was different than 101,325 Pa, correction values were applied to thermometer readings using reference data from [46].

The production of biofuels from solid waste with preliminary hydrolysis is mainly conducted with solid waste as an input material [47–52]. Given that the hydrolysis takes place at elevated temperatures (ex. 180, 220 and 260 °C [52]), acid evaporation into the environment occurs. Thus, the hydrolysis method requires pretreatment of raw materials with hydrochloric acid or alkali, which is harmful to the environment, and therefore was not used in our research methods.

Then, the gas burner was turned on and the heating of the flask was adjusted so that the first drop of fuel during distillation fell from the end of the cooling tube no earlier than 5 min and no later than 15 min from the start of heating. The temperature at which the first drop of condensate fell was recorded as the initial boiling temperature. After the first drop of fuel fell into the receiving cylinder, the heating was increased, and distillation was carried out at a uniform rate of 20–25 drops per 10 s, which corresponds to 4–5 mL/s.

The kinematic viscosity was measured with a maximum error of ±3% by a capillary viscometer VPZh-2 (LLC EximLab®, Kyiv, Ukraine) with a thermostat model SZhML-19/2.5-I1 (LLC Altavyr, Kyiv, Ukraine).

The density of alcohol and fuel mixtures was determined by an areometer ANT-2 (LLC Petroline, Kyiv, Ukraine) with a maximum error of ±1%.

For further testing the alcohol's properties as an additive to commercial gasoline, mixtures of A80-Euro-4 (DSTU 7687:2015) gasoline with the alcohol were prepared. Mixing of fuel alcohol with gasoline was carried out in a closed vessel with an electric stirrer—stirring mixtures for 5 min at a temperature of 20 °C. In total, 5 different mixtures were prepared, with vol. alcohol contents of 5, 10, 15, 20 and 25%, respectively. Prepared samples appeared as the alcohol completely dissolved in gasoline. They were afterwards kept in hermetically sealed glass vessels for 60 days at a temperature of 21 °C. No stratification or inhomogeneities were observed in the mixtures throughout their entire volume.

The sample liquids were afterwards characterized by octane number, content of water-soluble acids and alkalis and density at 20 °C. The mixtures' octane numbers were measured using the same method as previously used for pure alcohol.

The values of the parameters of all sample compositions were measured three times, and further construction of graphical dependencies and approximation curves was carried out using the average values of the measurements.

The analyzed fuel mixtures' density was examined at an ambient temperature equal to 23 °C, so the measured density value had to be corrected to its value at a temperature of 20 °C:

$$\rho^{20} = \rho^t + \gamma \cdot (t - 20), \tag{1}$$

where $\rho^t$ is the density value measured at a set temperature (in this case 23 °C) in $\frac{\mathrm{kg}}{\mathrm{m}^3}$ and $\gamma$ is the mean density change per 1 °C, in $\frac{\mathrm{kg}}{\mathrm{m}^3\mathrm{C}}$ in accordance with [46].

The sulfur content in the fuel was determined using an X-ray fluorescent energy dispersive sulfur analyzer Petra 4294 (XOS, East Greenbush, NY, USA) in accordance with ASTM D4294 standard [53], with measurement accuracy of ±3%.

## 3. Results and Discussion

The main physical and chemical parameters of fuels for gasoline internal combustion engines include octane number, density, kinematic viscosity, etc. Gasolines produced by catalytic cracking have octane ratings between 80 and 93, according to the motor method (motor octane rating—MOR), and to increase them, expensive high-octane components are used, the content of which can be up to 40%. To increase the octane number, improving vaporization point and performance, it is possible to use the obtained JA alcohol as an additive to commercial gasoline.

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The measured properties of the obtained alcohol are presented in Table 1. It is visible that the experimentally measured properties of obtained fuel alcohol are similar to, and even in some cases have higher values than, those of commercial gasoline. Therefore, the bioalcohol can be used as a low-cost additive.

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**Table 1.** Comparison of selected parameters for commercial A95 gasoline and JA alcohol.

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| n° | Property | Units | Values for A95 Gasoline | Values Measured for JA Alcohol |
|---|---|---|---|---|
| 1 | Octane rating:<br>RON<br>MON | -<br>- | 95<br>85 | 111<br>94 |
| 2 | Density | kg/m$^3$ | 720–775 | 786 |
| 3 | Kinematic viscosity | m$^2$/s | $1.2 \times 10^{-6}$ | $3.1 \times 10^{-6}$ |

Figure 3 shows the measured values of research octane number (RON) and motor octane number (MON) for fuel mixtures with different volumetric alcohol contents. Measured RONs are several units higher than MON, which is explained by the milder installation's operating conditions for determining RON, namely—lower engine crankshaft speed (10 rpm) and 13° ignition advance angle.

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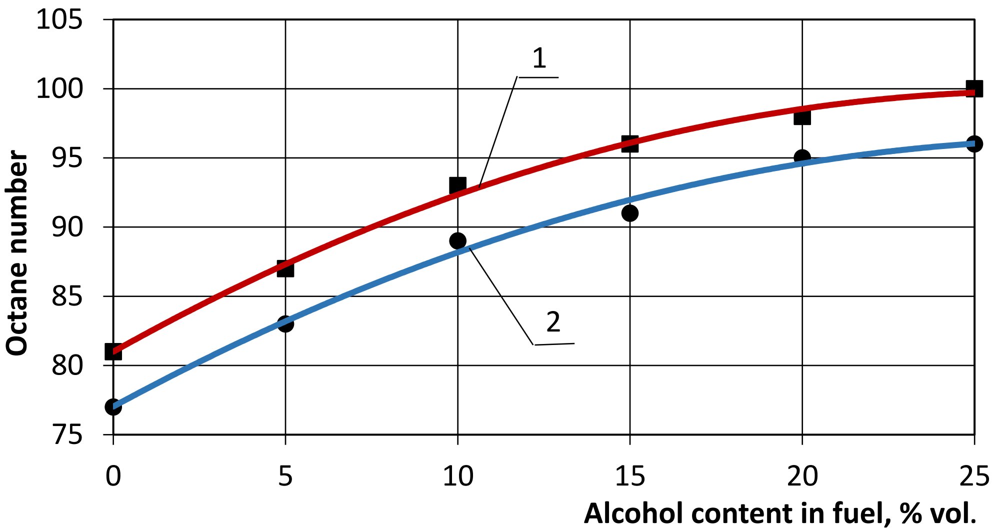

**Figure 3.** Relation between the octane number and volumetric alcohol content in the fuel mixture. 1—Research octane number (RON); 2—Motor octane number (MON).

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Dependencies presented in Figure 3 can be approximated by second-order polynomials:

$$MON = 81 - 0.0257V_C^2 + 1.3914V_C^2, \quad (2)$$

$$RON = 77.036 - 0.0236V_C^2 + 1.3493V_C. \quad (3)$$

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where MON is the octane number obtained by the motor method, RON is the octane number obtained by the research method and $V_C$ is the volumetric content of alcohol in the mixture, in %.

Based on the octane number values, authors established the optimal compositions of fuel mixtures to be alternatives for commercially available gasoline grades:

- The mixture of gasoline MON = 80 and 10% alcohol additive to obtain A92 grade,
- The mixture of gasoline MON = 80 and 15% alcohol additive to obtain A95 grade,
- The mixture of gasoline MON = 80 and 25% alcohol additive to obtain A98 grade.

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The calorific value of fuel is one of its main characteristics, as the energy released provides the driving force for an internal combustion engine. The change in the calorific value of fuel depending on the volume content of fuel alcohol was determined by the analytical method according to [54] and is shown in Figure 4. The analytical relation shown can be approximated by a second-order polynomial:

$$Q_n = 43.964 - 0.005V_C^2 + 0.1521V_C \quad (4)$$

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According to the results presented, with an increase in the volume content of fuel alcohol in gasoline to 25%, a decrease in the calorific value by 16% is observed, which is explained by the lower calorific value of fuel alcohol.

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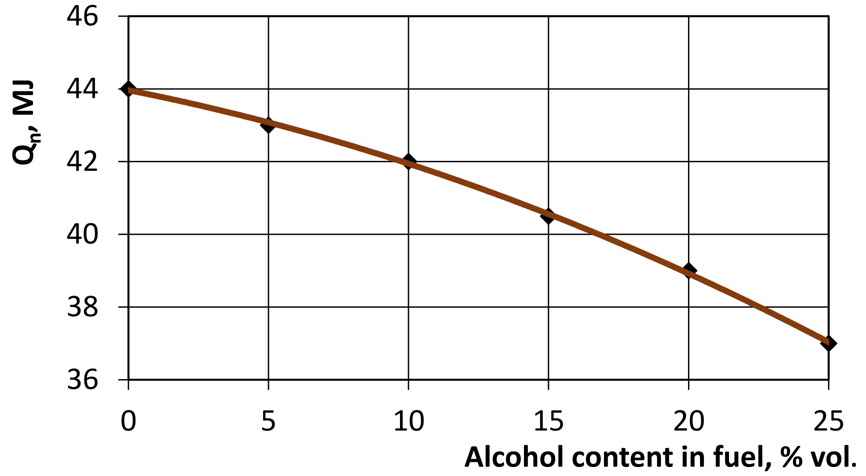

**Figure 4.** Relation between the calorific value of the mixture and volumetric alcohol content.

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The viscosity and density of the fuel significantly affect the fuel's flow through the fuel injector nozzles. The higher the viscosity of gasoline, the lower its volumetric flow rate, and as its density increases, its mass flow rate increases.

The density of gasoline also affects the composition of the combustible mixture and the quality of its preparation in the combustion chamber of an internal combustion engine, since too high a density leads to poor fuel mixing, as large-diameter droplets are formed that do not have time to completely burn in the chamber (mechanically incomplete combustion), increasing specific fuel consumption. Measured values of density and kinematic viscosity of fuel mixtures are shown in Figures 5 and 6.

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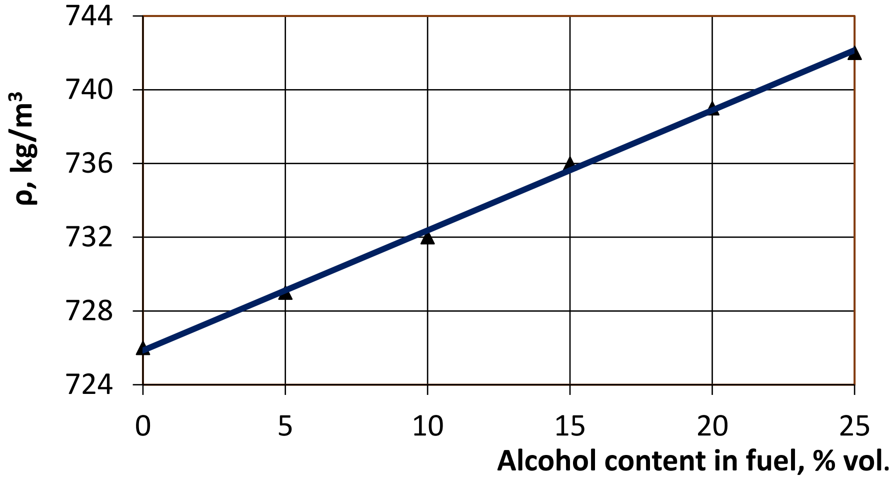

**Figure 5.** Relation between density of the fuel mixture and volumetric alcohol content.

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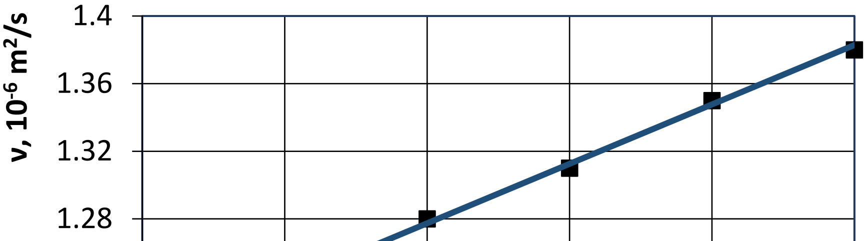

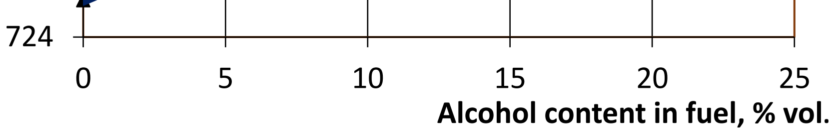

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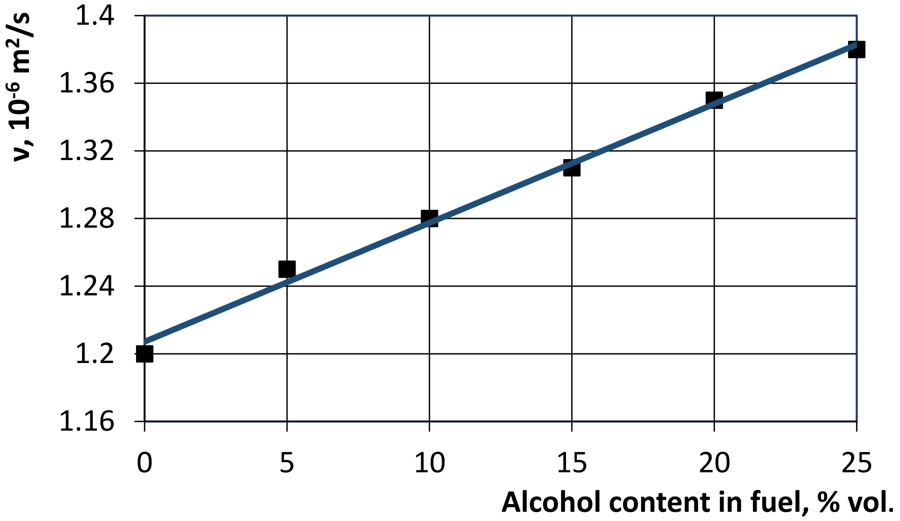

**Figure 6.** Relation between kinematic viscosity of the mixture and volumetric alcohol content.

The density and kinematic viscosity curves shown in Figures 5 and 6 can be approximated with the following formulas:

$$\rho = 725.86 + 0.6514V_C \tag{5}$$

$$\nu = 1.2071 + 0.007V_C \tag{6}$$

The density of commercially available gasolines varies between 720 and 775 kg/m³. The density of examined fuel mixtures ranges between 720 and 740 kg/m³. The small value of the coefficient next to $V_C$ in the kinematic viscosity formula (value of 0.007) indicates that the kinematic viscosity of the examined mixtures does not differ significantly from that of pure gasoline, leading to the conclusion that the addition of fuel alcohol to gasoline in an amount up to 15% of the volume will not adversely affect the pumpability of the mixture through the power system.

Equations (2)–(7) were obtained using the least squares method. The correlation coefficients were calculated according to the classical method, and for Equations (2)–(7) are within the range of 0.98–0.99.

An important indicator of the corrosive properties of fuels is their sulfur content. The effect of the addition of fuel alcohol to gasoline on its sulfur content is shown in Figure 7 and can be approximated by the following equation:

$$S = 8.5107 + 0.0046V_C^2 - 0.2486V_C \tag{7}$$

As can be seen in the figure, with the addition of 25% vol. of alcohol to gasoline, the sulfur content drops by 38%, visibly improving the quality of the fuel.

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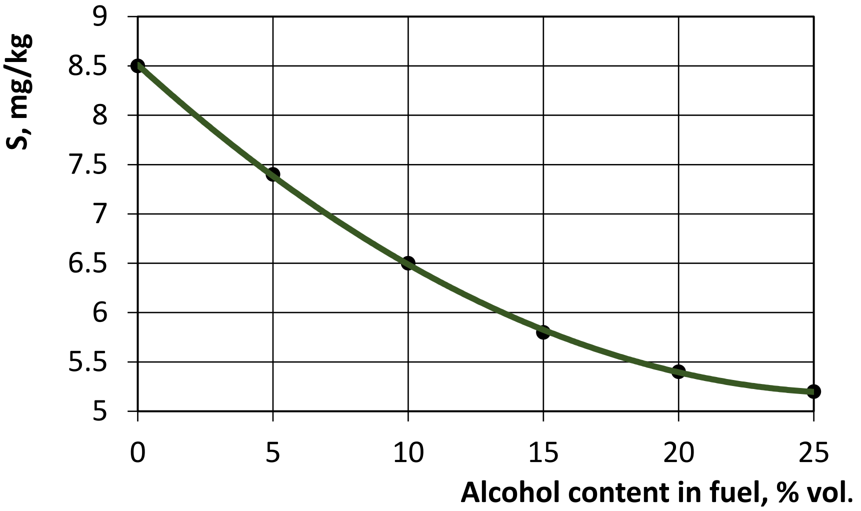

**Figure 7.** Fuel's sulfur content in relation to the percentage amount of alcohol additive.

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The determined vaporization temperature of the fuel with 25% vol. alcohol additive is shown in Figure 8. For commercially available gasoline, the volume fraction of evaporation at 70, 100 and 150 °C and the volume of residue in the flask is standardized. The ease of starting the engine is characterized by the volume fraction of evaporation at a temperature of 70 °C. As can be seen in the figure, the mentioned volume at this tem-

he correlation
ions (2)–(7) are
within the range of 0.98–0.99.

**Figure 7.** Fuel's sulfur content in relation to the percentage amount of alcohol additive.

As can be seen in the figure, with the addition of 25% vol. of alcohol to gasoline, the sulfur content drops by 38%, visibly improving the quality of the fuel.

The determined vaporization temperature of the fuel with 25% vol. alcohol additive is shown in Figure 8. For commercially available gasoline, the volume fraction of evaporation at 70, 100 and 150 °C and the volume of residue in the flask is standardized. The ease of starting the engine is characterized by the volume fraction of evaporation at a temperature of 70 °C. As can be seen in the figure, the mentioned volume at this temperature increased in comparison to pure gasoline by 17.5%, which can facilitate engine startup and reduce its wear speed.

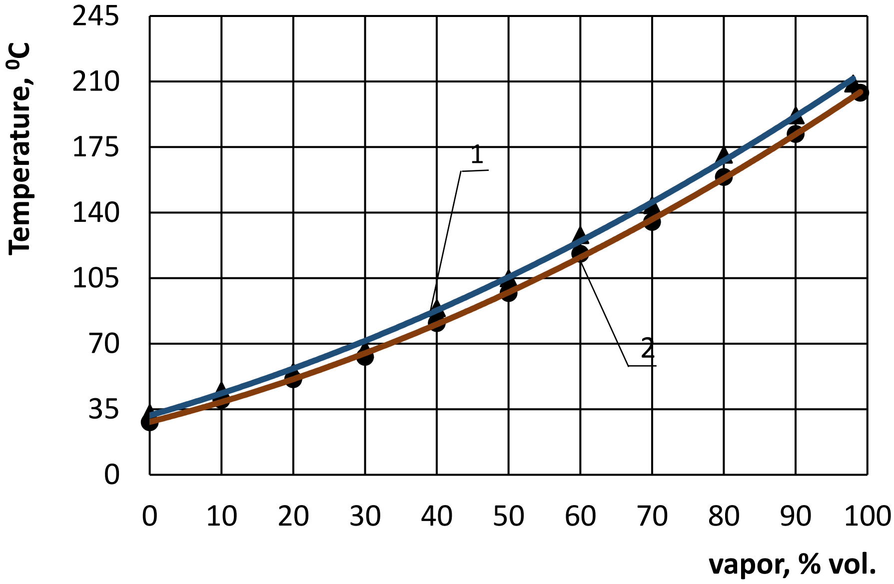

**Figure 8.** Relation between fuel evaporation volume and temperature. 1—pure A95 gasoline; 2—Mixture of A95 gasoline and 25% bioalcohol.

Engine warm-up, dynamism, acceleration to a certain speed after a sharp throttle opening and ability to overcome hills without shifting gears depend mainly on the distillation volume at a temperature of 100 °C. With the addition of fuel alcohol, the distillation volume at 100 °C increased by 10.5%, which can ensure stable engine operation at low crankshaft speeds and good meshing. The temperature of 150 °C and the final boiling point of gasoline characterize the composition of the working mixture in the cylinder at the end of the compression stroke, the completeness of fuel combustion, the ease of transition from light to full loads and vice versa, engine operation, fuel and engine oil consumption and the composition of exhaust gases. According to the research results, this indicator is practically the same as its value for gasoline, which means that the reliability of engine operation will not decrease.

Important results were obtained in the study [55], where a mixture of gasoline and waste from the alcohol industry—fusel oil—is proposed as fuel. In this research, it was found that the concentration and depth of penetration of heavy metals into the soil decrease with an increase in the content of fusel oil in the fuel. Therefore, important aspects of our further research are the environmental indicators of the obtained alcohol fuel and the utilization of waste materials from manufacturing process.

In studies [56,57], authors proposed to produce pyrolysis fuel gas from solid waste. It was established that during the pyrolysis of aquatic plants and algae, the mixture of obtained gases had the highest values of lower heating value: 17.10–17.15 MJ/kg for microcystis and 16.45–16.00 MJ/kg for elodea. The gas obtained from pine wood pyrolysis had the highest values of lower heating value in the range of 13.8 to 13.85 MJ/kg. The lower heating value of pyrogas obtained from samples of reeds ranged from 12.6 MJ/kg to 12.65 MJ/kg. Therefore, a promising direction of research is the use of Jerusalem artichoke biomass waste in pyrolysis plants for biogas production.

Biomass conversion technologies are developed nowadays, due to their potential in reducing carbon emissions as well as the dependence on oil, thanks to the renewable character of the raw source material [58]. The European biofuel market is especially potent in terms of development due to its current low input into the world's biofuel production—notably holding only 6% of the world's market share currently [59].

To ensure effective use of alcohol fuel in the future, it is necessary to ensure quality fuel mixture formation and ignition in the cylinders of internal combustion engines (ICEs). Further research should be conducted on engines with a turbocharging system to ensure good fuel-air mixture formation and ignition. Additionally, further research should focus on identifying the impact of alcohol fuel on the ecological parameters of internal combustion engine (ICE) operation within hybrid powertrains with parallel and series operating schemes.

## 4. Conclusions

The research conducted provides a basis for further research into JA tubers as a biomass source for bioethanol manufacturing, as well as obtaining ethanol-gasoline blends from the manufactured alcohol, corresponding to standardized A92, A95 and A98 fuels. The alcohol yield of 0.85 L from 10 kg of JA tubers is considered satisfactory, given the low cultivation requirements of the plant.

The calorific value of the obtained blend (25% ethanol, 75% MON 80 gasoline) was decreased by 16% in comparison to A98 pure gasoline, which might affect energy efficiency, but said downside is offset by the biofuel's cleaner combustion, better source material sustainability and lower costs of obtaining high octane fuel.

A significant reduction of sulfur content, namely by 38% in the 25% ethanol blend (E25), can help to reduce the corrosive properties of biofuel and potentially increase the lifespan of engine components, in effect decreasing maintenance costs.

Improved vaporization of the E25 fuel mixture (by 17.5% at 70 °C and by 10.5% at 100 °C) can help reduce engine startup strain as well as ensure stable operation in stop-and-go in urban traffic conditions.

In the future, additional follow-up research can be conducted to determine how the obtained biofuel performs in different types of gasoline engines, analyzing performance and exhaust gasses' contents in comparison to pure gasoline. Research might also be conducted on the scalability of bioalcohol production from JA.

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