

Article

Analysis of Energy Potential of Switchgrass Biomass

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Abstract: In this research, the energy potential of switchgrass (SG) was analyzed to find promising directions for producing bioenergy from this biomass. The first direction is determining the thermal energy of bioethanol extracted from SG biomass after its pretreatment, enzymatic hydrolysis (saccharification), and fermentation of the resulting glucose. It was established that after a two-stage pretreatment of 1 ton of SG with dilute solutions of nitric acid and alkali, the largest amount of bioethanol can be extracted with an energy potential of 4.9 GJ. It is also shown that by the utilization of solid and liquid waste, the production cost of bioethanol can be reduced. On the other hand, the direct combustion of 1 ton of the initial SG biomass used as a solid biofuel provides an increased amount of thermal energy of 18.3 GJ, which is 3.7 times higher than the energy potential of the resulting bioethanol extracted from 1 ton of this biomass. Thus, if the ultimate goal is to obtain the maximum energy amount, then another direction for obtaining bioenergy from biomass should be implemented, namely, direct combustion, preferably after pelletizing. Studies have shown that fuel characteristics of SG pellets such as the gross thermal energy and density of thermal energy are lower than those of wood pellets, but they can be improved if the SG biomass is densified into pellets together with binders made from polymer waste.

Keywords: bioenergy potential; bioethanol; biomass; pretreatment; saccharification; fermentation; fuel pellets



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1. Introduction

Rising prices for fossil fuels and the need to reduce greenhouse gas emissions, along with energy security, stimulate the use of alternative energy sources, including bioenergy, a promising source of which is the biomass of energy crops such as switchgrass (SG) [1,2]. SG is a perennial warm-season grass of the *Panicum virgatum* variety that grows in North and Central America. The height of the grass can reach 2.7 m. The typical annual yield of SG is 10 to 20 dry tons per ha. This crop can grow on marginal lands for ten years and requires a relatively low level of fertilizers. Overall, SG is considered a resource-efficient, low-input crop for producing bioenergy from marginal farmlands [3,4].

The biomass of any plant is formed in nature from carbon dioxide and water by photosynthesis-absorbing solar energy [5]. Thus, a plant biomass is an accumulator of solar energy captured during photosynthesis. When the plant biomass is burned, this results in the release of the accumulated solar energy, along with water and carbon dioxide [6]. Therefore, biomass is considered a CO₂-neutral renewable natural source [6,7].

Nowadays, three main directions for producing bioenergy from biomass are known. The first direction is the pyrolysis of biomass for its transformation into bio-oil, biogas, and biochar [8–10]. However, this direction is energy-consuming and requires the use of fossil energy sources that can be accompanied by pollution of the environment and emission of greenhouse gases and aerosols. It has been established that the liquid product of biomass pyrolysis, bio-oil, contains various harmful organic substances, such as furan derivatives, aldehydes, ketones, phenols, organic acids, methanol, etc. [8]. Due to its acidic pH, this liquid product corrodes equipment. On the other hand, biogas contains harmful carbon oxide and greenhouse carbon dioxide [9,10]. In addition, bio-oil, biogas, and torrefied solid residues are heterogeneous, low-quality products having relatively low calorific values.

The second direction is the burning of biomass to generate bioenergy. However, the initial biomass is a non-dense and heterogeneous material that can consist of pieces of various sizes with different calorific values. Moreover, it can contain moisture and inorganic admixtures. These features of the initial biomass cause serious problems with the burning of this solid biofuel, namely, the moisture and inorganic components decrease the calorific value, while the low bulk density of the initial biomass leads to a reduced energy density and combustion efficiency [11–13]. In addition, the increased moisture and the content of inorganic admixtures, especially with a lack of air, lead to the incomplete combustion of biomass over an open fire and the formation of harmful aerosol microparticles [14]. However, when the biomass is burned in combustion chambers equipped with special smoke filters, these microparticles are captured, which prevents air pollution [15].

If the biomass samples are burned in a calorimetric bomb in an oxygen atmosphere, the amount of microparticles can be minimized. In addition, these microparticles cannot escape from the closed bomb and pollute the environment.

To improve the fuel performance, the biomass must have a reduced content of inorganic admixtures and moisture, as well as an increased density. For this purpose, the biomass before burning should be demineralized, dried, and densified into pellets [11,12]. In addition, it was found that the addition of polyolefins (e.g., PE, etc.) to biomass increases the calorific value of resulting fuel pellets [7,13].

The third direction for producing bioenergy from biomass is its hydrolysis with cellulolytic enzymes to glucose, followed by fermentation to produce bioethanol, which is applied as a renewable liquid biofuel [16,17]. Features of the enzymatic hydrolysis of various plant materials have been discussed in many studies [18–22]. To implement the effective hydrolysis of biomass, enzyme preparations were used, which include at least three types of specific enzymes, such as endo-1,4- β -glucanases, exo-1,4- β -glucanases, and β -glucosidases. These enzymes act synergistically, because endo-acting enzymes generate new chain ends for the exo-acting enzymes, which release the oligosaccharides that are converted into glucose by β -glucosidases [20].

The enzymatic hydrolysis of biomass is usually carried out at a temperature of 50 °C and pH 4.5–5.5 using a dose of enzyme preparation of 10 to 40 mg of protein per 1 g of substrate. It has been found that to achieve maximum glucose concentration during enzymatic hydrolysis, the optimal loading of the cellulose-containing substrate in the aqueous enzyme system should be at least 150 g/L [20–22]. At a higher substrate loading, enzymatic hydrolysis ceases due to a significant reduction in the mass transfer and inhibition of cellulolytic enzymes by a large amount of formed glucose [23].

In addition, it was established that the initial plant biomass exhibits high resistance to enzymatic cleavage due to the compact structure of the plant material and the presence of non-cellulosic components hindering the hydrolysis process. Therefore, the plant biomass is pretreated to loosen its physical structure, eliminate non-cellulosic components, and increase cellulose accessibility to cellulolytic enzyme molecules. To reduce biomass recalcitrance, various pretreatment methods can be used such as steam explosion, acid hydrolysis, alkaline extraction, oxidation, and combined methods [24–30]. After the acidic pretreatment of the biomass, predominantly hemicelluloses are removed, which leads to an increase in the cello-lignin content. During alkaline and oxidative pretreatments, a partial removal of hemicelluloses and lignin from the biomass occurs, which is accompanied by an increase in the cellulose content in the pretreated biomass and a reduction of biomass recalcitrance to enzymatic hydrolysis. Combined pretreatment methods are considered the most effective for removing non-cellulosic components from biomass and improving enzymatic hydrolyzability. As is known, after the enzymatic hydrolysis of the pretreated biomass, an unhydrolyzed residue always remains, which must be utilized, for example, by combustion, to prevent environmental pollution.

The main purpose of this research was to disclose the energy potential of SG and choose the most optimal method for producing bioenergy from this biomass. Namely, the

amount of combustion energy of the initial SG biomass and bioethanol extracted from this biomass after its pretreatment, enzymatic hydrolysis, and fermentation are compared.

2. Materials and Methods

2.1. Materials

Switchgrass (SG) was supplied from Nott Farms (Clinton, ON, Canada). The SG sample was dried, crushed in a knife mill, and screened to select the fraction with a size of 2 mm. Powdered wastes of polystyrene (PS) and polyethylene (PE) with a size of 3–5 mm were acquired from Amnir Recycling Industries (Hadera, Israel). The needed pure chemicals (96% sulfuric acid, 70% nitric acid, NaOH, peptone, KH_2PO_4 , and $(\text{NH}_4)_2\text{SO}_4$) were purchased from Sigma-Aldrich (St. Louis, MO, USA).

2.2. Pretreatments

The SG samples were pretreated with boiling 3 wt.% of sulfuric acid (AC pretreatment) and with boiling 2 wt.% of sodium hydroxide (AL pretreatment). The samples were put in lab glasses, after which the reagent solution was added to a liquid/solid ratio of about 7. The glasses containing the biomass and reagent were placed into an oil bath at a temperature of 110 °C and treated at stirring for 1 h. The pretreated biomasses were washed up to a neutral pH and squeezed on a vacuum glass filter to a solid content of 25–30 wt.%.

The combined acid-alkaline (AA) pretreatment of SG was carried out in two steps [27]. In the first step, the initial biomass was placed in a hermetically sealed glass reactor and treated with 5 wt.% of nitric acid at a liquid/solid ratio of 5 and at a temperature of 115 °C for 1 h without stirring. The acid-treated biomass was washed to a neutral pH value and squeezed on a vacuum glass filter to a final solid content of 25–30 wt.%. In the second step, the semi-finished biomass from the first step was treated with boiling 2 wt.% of sodium hydroxide at a liquid/solid ratio of 7, while stirring for 1 h. Then, the treated biomass was washed to a neutral pH and squeezed on a vacuum glass filter to a solid content of 25–30 wt.%.

To determine the yield of the pretreated biomass, a small part of the wet sample was dried at 105 °C to a constant weight, and the determined moisture content was used to calculate the dry weight of the pretreated biomass.

2.3. Analysis of Chemical Composition

The chemical composition of the biomass samples was performed by standard NREL analytical methods to find the content of cellulose, hemicelluloses, lignin, and some other components [31]. Each analysis was repeated three times, and the standard deviation was calculated.

2.4. Enzymatic Hydrolysis

The pretreated biomass (PTB) samples were hydrolyzed by a commercial enzyme preparation Cellic CTec-3 (Novozymes A/S, Bagsvaerd, Denmark), containing endo-1,4-glucanases, exo-1,4-glucanases (EXG), and β -glucosidases. The dosage of Cellic CTec-3 was 30 mg per gram of dry sample. Samples were placed into glass flasks and supplemented with the required amount of the enzyme and 50 mM of an acetate buffer (pH 4.8) to provide a substrate loading (C_s) of 150 g/L [20–22]. The hydrolysis was performed at 50 °C for 10–120 h with a constant shaking of 150 rpm. The residual biomass remaining after the enzymatic hydrolysis of the PTB was separated from the glucose solution by centrifugation at $5000 \times g$ for 10 min, washed several times with water, and dried at room temperature in a ventilated area to a moisture content of 10–14 wt.% and then at 105 °C to a constant weight.

The glucose concentration was determined by HPLC using an Agilent 1200 Infinity Series system (Agilent Technologies, Santa Clara, CA, USA) with an Amines HPX-87H column. The mobile phase was 0.005 M of sulfuric acid, and the flow rate was 0.6 mL/min at 45 °C. Hydrolyzed samples were preliminarily filtered through a 0.45 μm nylon filter.

The yield of glucose from the biomass was calculated using the following equation:

$$Y = C/C_s \quad (1)$$

where C (g/L) is the experimental concentration of the glucose after hydrolysis of the sample, and C_s is the loading of the substrate (150 g/L).

Each analysis was repeated three times, and the standard deviation of the glucose yield was calculated, which did not exceed ± 0.05 .

2.5. Fermentation

The fermentation of the glucose solutions obtained after the enzymatic hydrolysis of the pretreated biomass samples was carried out by the yeast of *Saccharomyces cerevisiae* at 30 °C and pH = 4.5, while shaken at 150 rpm for 3 days. Peptone (0.2%), KH_2PO_4 (0.1%), and $(\text{NH}_4)\text{SO}_4$ (0.1%) were added to improve the growth of the yeast. The medium was pre-sterilized at 120 °C for 20 min. After finishing the fermentation, the broth was transferred to Eppendorf tubes and centrifuged at $5000 \times g$ for 10 min to remove the yeast cells.

The concentration of the ethanol formed after the fermentation stage was determined by the gas chromatography method, using a GC-FID model 8610 C of SRI. The oven and column temperatures were initially set at 50 °C and held constant for 2 min and then elevated at the rate of 5 °C/min, giving a total run time of 10 min. The injector temperature was held at 250 °C. The flow rate of H_2 was 25 mL/min and air 100 mL/min. The carrier gas was N_2 , with a constant pressure of 1.7 atm. The sample with a volume of 2 μL was injected using a 5 μL syringe. Each injection was repeated three times.

The amount of produced ethanol was calculated as follows:

$$\text{ET} = V_b C_{\text{et}}, \quad (2)$$

where C_{et} is the concentration of ethanol (g/mL), and V_b is the volume of the broth (mL).

Each experiment was repeated three times, and the standard deviation of ET was calculated.

2.6. Amount of Thermal Energy

The combustion of the biomass samples in pelletized form was carried out at 25 °C in a bomb calorimeter Parr (model 6400) at an oxygen pressure of 3 MPa with 1 mL of added deionized water. The temperature was measured with an accuracy of ± 0.001 degrees. The value of the energy equivalent of the calorimetric system was determined by the combustion of standard benzoic acid. The true mass of the sample used in each experiment was determined from the mass of the produced CO_2 . The correction of the combustion energy for ignition and some other corrections were considered. To adjust the experimental combustion energy to standard conditions, the Washburn correction was introduced. Finally, to calculate the final amount of gross thermal energy (Q), the correction for the change in the number of moles of gases before and after combustion was introduced.

In addition, the density of thermal energy was calculated:

$$E = Q \times d \quad (3)$$

where Q is the amount of gross thermal energy (MJ/kg), and d is the density of the sample (kg/m^3).

The testing of each sample was repeated three times. The standard deviations were calculated, which did not exceed $\pm 2\%$.

3. Results

The chemical compositions of the initial biomass (IN) and biomass samples pretreated by the AC, AL, and AA methods are shown in Table 1.

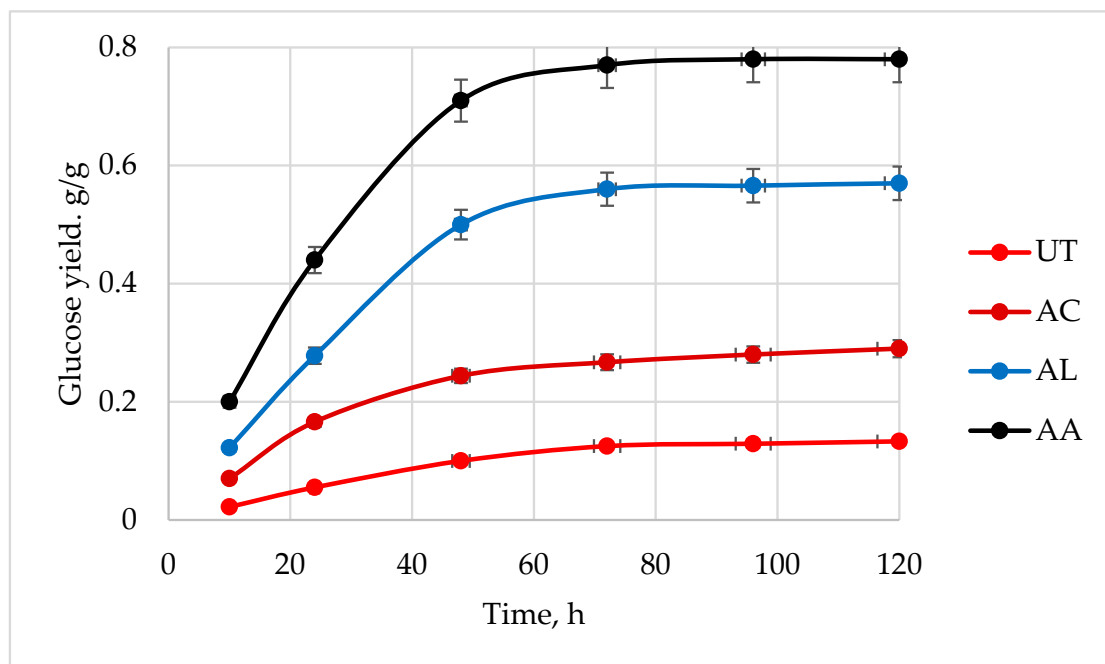
Table 1. Percentage content (wt.%) of components in initial and pretreated biomass samples.

Components	IN	AC	AL	AA
Cellulose	37 ± 2	55 ± 2	66 ± 2	92 ± 2
Hemicelluloses	28 ± 2	7 ± 1	15 ± 1	2 ± 0.2
Lignin	19 ± 2	28 ± 2	12 ± 1	3 ± 0.2
Extractives	7 ± 1	2 ± 0.2	2 ± 0.2	1 ± 0.1
Protein	5 ± 0.5	6 ± 0.5	2 ± 0.2	1 ± 0.1
Ash	4 ± 0.5	2 ± 0.2	3 ± 0.2	1 ± 0.1
Yield of PTB	100 ± 1	67 ± 1	56 ± 1	41 ± 1

The acidic pretreatment of the initial SG causes the removal of most hemicelluloses and produces cello-lignin, with an increased content of cellulose and lignin. As a result of alkaline pretreatment, both hemicelluloses and lignin are partially extracted, which leads to an increase in the cellulose content in the PTB.

The combined AA-pretreatment method makes it possible to remove the main part of the non-cellulose components from the initial SG and prepare PTB with the highest cellulose content, 92 wt.%. Naturally, the yield of PTB after AA is significantly reduced to 41 wt.%.

Kinetic studies of the enzymatic hydrolysis of SG samples have shown (Figure 1) that at least three days are required to achieve the final yield of glucose (GL) from biomass samples. In the case of the untreated SG sample (UT), the final yield of GL was minimal, while the final yield of GL from the AA-pretreated biomass containing 92 wt.% of cellulose was the highest, at about 0.78 g/g.

**Figure 1.** Kinetical curves of enzymatic hydrolysis of untreated and pretreated SG samples.

If using untreated (UT) SG biomass, then after the stages of saccharification and fermentation, the yield of bioethanol will be minimal. On the other hand, the AA pretreatment of the biomass contributed to obtaining the maximum yield of this liquid biofuel after the stages of saccharification and fermentation (Table 2). In addition, after the stages of pretreatment, saccharification, and fermentation of the initial SG, residual biomass (RB) remained with the yield of Y(RB).

Table 2. Yield of ethanol, Y(ET), and residual biomass, Y(RB), from initial SG.

Pretreatment	Y(ET), %	Y(RB), %
UT	6.6 ± 1.8	87.0 ± 0.4
AC	8.9 ± 1.7	46.9 ± 0.5
AL	14.6 ± 1.4	28.0 ± 0.8
AA	16.3 ± 1.3	10.3 ± 1.1

Using data from Table 3, the bioenergy potential of the resulting bioethanol was evaluated as follows:

$$Q = q \times ET \quad (4)$$

where $q = 30 \text{ kJ/g}$ is the gross energy of ethanol combustion, and ET is the amount of ethanol extracted from the initial SG after the stages of pretreatment, saccharification, and fermentation.

Table 3. The amount of thermal energy obtained from the combustion of extracted ethanol.

Pretreatment	ET, g	Q, MJ
UT	66.4 ± 1.2	1.99 ± 0.04
AC	89.0 ± 1.5	2.67 ± 0.05
AL	146.0 ± 2.0	4.38 ± 0.06
AA	163.4 ± 2.2	4.90 ± 0.07

The obtained results are presented in Table 3.

A study of the combustion of solid plant materials showed that 1 kg of an initial SG biomass (IN) has a great thermal energy of about 18.3 MJ (Table 4). During bioethanol production, the amount of the residual biomass decreased, and, therefore, the amount of thermal energy released after the combustion of RB was also reduced.

Table 4. Amount of thermal energy (Q) obtained from initial (IN) and residual (RB) biomass samples.

Pretreatment	RB, g	Q, MJ
IN	1000	18.30 ± 0.05
UT	870.0 ± 2.8	16.18 ± 0.06
AC	469.3 ± 2.4	8.92 ± 0.05
AL	280.1 ± 2.1	5.29 ± 0.04
AA	103.2 ± 2.0	1.90 ± 0.04

4. Discussion

From the results, it follows that the amount of obtained bioethanol depends on the method of pretreatment of the biomass before enzymatic hydrolysis. The untreated and AC-pretreated biomass samples show a relatively small yield of alcohol, while the biomass pretreated with the AA method produced the maximum amount of liquid biofuel. Simultaneously with the increase in the ethanol yield, the amount of thermal energy in this liquid biofuel also increases, reaching 4.9 MJ (Table 3).

Thus, if the ultimate goal is to produce liquid biofuel such as ethanol from inedible plant biomasses, then it is preferable to use the AA or similar pretreatment method that provides the highest content of cellulose in the PTB and the maximum amount of formed ethanol along with a minimum of solid waste. Studies have shown that if this waste is utilized by incineration, it is possible to obtain an additional thermal energy of about 1.9 MJ, if the weight of the initial biomass is 1 kg (Table 4). However, if the weight of the initial

SG is 1 ton, then the amount of additional thermal energy from RB burning will be 1.9 GJ, which can reduce the production cost of bioethanol by approximately USD 79.2.

Another possibility for reducing the cost of bioethanol production is to use liquid waste from the pretreatment stage to obtain and sell a by-product. As indicated in Section 2.2, the pretreatment of SG with the AA method included sequential treatment of this biomass with solutions of nitric acid and alkali. After such a pretreatment, the used acidic and alkaline liqueurs were mixed and neutralized each other, resulting in the formation of a combined liquor, a by-product containing sodium nitrate, nitrolignin, and oligosaccharides, which can serve as a valuable agricultural fertilizer. After pretreatment of 1 ton of an SG biomass, about 12 tons of the by-product can be obtained.

To evaluate the pretreatment cost of 1 t of SG, the costs of the initial biomass, chemicals, water, energy consumption, etc., were taken into account (Tables 5 and 6).

Table 5. Cost of feedstock, chemicals, water, and electric energy.

Item	Cost
SG feedstock	USD 50 per t
70% HNO ₃	USD 250 per t
NaOH	USD 210 per t
Water	USD 0.8 per m ³
Electricity	USD 150 per MWh

Table 6. Expenses for AA pretreatment of biomass.

Item	Amount	Cost, USD
Feedstock	1 ton	50
4% of HNO ₃	5 ton	71
1.5% of NaOH	7 ton	21
Water	10 t	8
Energy	2 MWh	300
	Subtotal 1:	450
Overheads	15%	67.5
	Subtotal 2:	517.5
Selling of by-products	12 ton	600
	Income	82.5

If you sell the by-product (combined liquor) at a low price of USD 50 per ton, you can cover pretreatment expenses and make an income of about USD 82.5. Considering the income of USD 79.2 from burning RB, the total cost of bioethanol production from 1 ton of biomass can be reduced by USD 161.7.

It can be calculated that from 1 ton of SG biomass after AA pretreatment and fermentation, one can obtain 54.6 gallons of bioethanol at a price of about USD 4 per gallon [8]; thus, the cost of such a volume of liquid biofuel will be USD 218.4. However, if we take into account the reduction in costs after the utilization of liquid and solid waste, the production cost of SG bioethanol can drop to USD 1.04 per gallon, which is even lower than the production cost of corn ethanol [8].

It has been established that the combustion of 1 ton of the initial SG biomass used as a solid biofuel provides an increased amount of bioenergy of about 18.3 GJ, which exceeds the energy potential of 4.9 GJ of the resulting bioethanol. Thus, if the ultimate goal is to obtain the maximum amount of bioenergy, then another direction for obtaining energy from biomass should be implemented, namely, direct combustion.

However, the initial SG biomass has a low bulk density ($80\text{--}100\text{ kg/m}^3$) and consists of constituents with different contents of biopolymers, moisture, and inorganic admixtures, thus having various calorific values. These negative features of the SG biomass lead to a deterioration in fuel performances during combustion—a variable calorific value ($15.8\text{--}18.5\text{ GJ/t}$), a low thermal energy density ($1.4\text{--}1.8\text{ GJ/m}^3$), and insufficient combustion efficiency. To improve fuel characteristics, the initial SG biomass must be dried and densified into pellets. For this purpose, the milled SG was dried and mixed with 10 wt.% of a binder, such as potato starch (ST), powdered waste polystyrene (PS), or polyethylene (PE), and then pressed in Pellet Press PP 40 (Retsch GmbH, North Rhine-Westphalia, Germany) under a pressure of 50 MPa and a temperature of $120\text{ }^\circ\text{C}$.

As is known, the consumption of wood-based fuel pellets (WPs) in the world is growing rapidly [32]. The global wood pellet market size was at USD 8.55 billion in 2022. The wood pellet market will grow at a CAGR of 5.5% and can reach USD 13.38 billion by 2030. The annual demand for pellets in Europe reached 24 million tons in 2020. Over 10 years, pellet consumption in the USA increased by 1.7 times and in China by more than 10 times. The wood pellets have good fuel performances with a gross combustion heat of $19\text{--}21\text{ GJ/t}$ and a thermal energy density of $12\text{--}14\text{ GJ/m}^3$ [33,34].

This study showed that the initial unpressed (UPR) SG sample had unsatisfactory fuel properties. However, SG pellets also densified without a binder (SGP_0) or with an ST binder (SGP_{st}) contained $1.5\text{--}2\text{ GJ/t}$ of less gross energy (Q) and $4.7\text{--}5\text{ GJ/m}^3$ of less density of thermal energy (E) than wood pellets (Table 7).

To improve the characteristics of SG pellets, a small amount (10 wt.%) of synthetic polymer binders (PS and PE) was added instead of starch. The obtained results reveal that the supplementation of such polymer binders to SG biomass enhances both the calorific value and thermal energy density of the resulting fuel pellets. As a result, these pellets acquire fuel performances of the best types of wood pellets (Figure 2).

In addition, the utilization of waste plastics as binders can promote the reduction in environmental pollution.

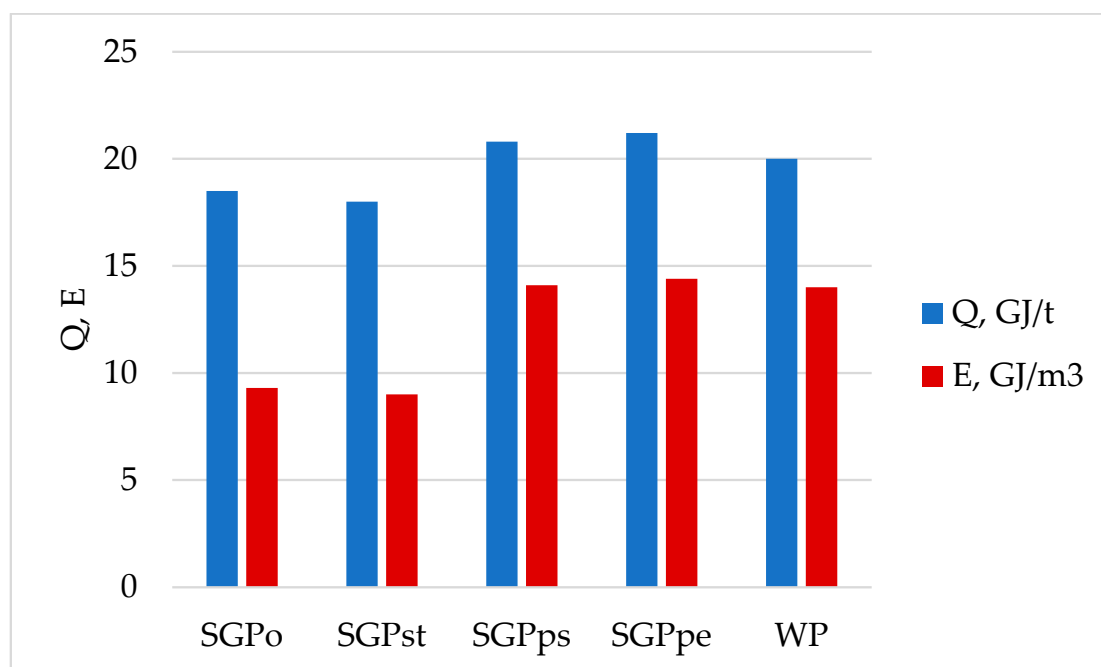


Figure 2. Values of gross energy (Q) and thermal energy density (E) for fuel pellets made from switchgrass (SGP) and wood (WP).

Table 7. Fuel characteristics of SG pellets: values of gross energy (Q) and thermal energy density (E).

Name of Pellets	Binder	Q, GJ/t	E, GJ/m ³
UPR	0	18.3 ± 0.1	1.8 ± 0.1
SGP _o	0	18.5 ± 0.3	9.3 ± 0.2
SGP _{st}	ST	18.0 ± 0.2	9.0 ± 0.3
SGP _{ps}	PS	20.8 ± 0.4	14.1 ± 0.3
SGP _{pe}	PE	21.2 ± 0.2	14.4 ± 0.2
* WP	uk	20	14

* Note: averaged data for wood pellets (WPs) from [32,33]; uk denotes unknown.

5. Conclusions

The energy potential of SG biomass was studied to find promising directions for bioenergy production. Two main directions for obtaining thermal energy from SG were considered. The first direction is the combustion of bioethanol extracted from the SG biomass after its pretreatment, enzymatic saccharification, and fermentation of the resulting glucose. It was found that the amounts of extracted bioethanol and thermal energy depend on the method of pretreatment of the biomass. The untreated and AC-pretreated biomass samples exhibited a relatively small yield of alcohol of 7–9%, while the biomass pretreated with the AA method provided the maximum bioethanol yield above 16%. Moreover, the resulting liquid biofuel obtained after the AA pretreatment of 1 t of the initial SG biomass followed by saccharification and fermentation had an increased energy potential of 4.9 GJ.

To provide the maximum yield of liquid biofuel (of about 54.6 gallons from 1 t of the biomass), it is preferable to use the AA or a similar pretreatment method before the saccharification and fermentation stages. It was shown that due to the utilization of solid and liquid waste, the production cost of SG-based bioethanol can be reduced and may even be lower than the production cost of corn ethanol.

From the obtained results, it also follows that 1 ton of the initial SG biomass has an increased amount of thermal energy of 18.3 GJ, which exceeds the energy potential of 4.9 GJ of the resulting amount of bioethanol extracted from 1 ton of biomass. Thus, if the ultimate goal is to obtain the maximum amount of bioenergy, then another direction for obtaining energy from biomass should be implemented, namely, direct combustion.

However, the initial SG biomass has unsatisfactory fuel performances such as a low calorific value and density of thermal energy. Studies have shown that these fuel characteristics can be improved if the SG biomass is compacted into pellets together with binders made from polymer waste. As a result, these pellets acquire fuel performances of the best types of wood pellets with a gross energy value above 20 GJ/t and a thermal energy density above 14 GJ/m³.

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Conflicts of Interest: Author Michael Ioelovich is employed by the company Designer Energy Ltd. The author declares no conflicts of interest, namely, no personal or collaborative conflicts, no professional or commercial conflicts, or any other conflicts of interest.

References

- Samson, R.; Mani, S.; Boddey, R.; Sokhansanj, S.; Quesada, D.; Urquiaga, S.; Reis, V.; Lem, C.H. The potential of C4 perennial grasses for developing a global bioheat industry. *Crit. Rev. Plant Sci.* **2005**, *24*, 461–495. [\[CrossRef\]](#)
- Ibitoye, S.E.; Mahamood, R.M.; Jen, T.C.; Loha, C.; Akinlabi, E.T. An overview of biomass solid fuels: Biomass sources, processing methods, and morphological and microstructural properties. *J. Bioresour. Bioprod.* **2023**, *8*, 333–360. [\[CrossRef\]](#)
- Schmer, M.R.; Vogel, K.P.; Mitchell, R.B.; Perrin, R.R. Net energy of cellulosic ethanol from switchgrass. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 464–469. [\[CrossRef\]](#)
- Sanderson, M.A.; Reed, R.L.; McLaughlin, S.B.; Wullschleger, S.D.; Conger, B.V.; Parrish, D.J.; Wolf, D.D.; Taliaferro, C.; Hopkins, A.A.; Ocumpaugh, W.R.; et al. Switchgrass as a sustainable bioenergy crop. *Bioresour. Technol.* **1996**, *56*, 83–93. [\[CrossRef\]](#)
- Blankenship, R.E. *Molecular Mechanisms of Photosynthesis*, 2nd ed.; John Wiley & Sons: Oxford, OH, USA, 2014; p. 312.
- Zeller-Powel, C.E. Defining Biomass as a Source of Renewable Energy: The Life-Cycle Carbon Emissions of Biomass Energy and a Survey and Analysis of Biomass Definitions in States' Renewable Portfolio Standards, Federal Law, and Proposed Legislation. Master's Thesis, University of Oregon, Eugene, OR, USA, 2011; p. 97.
- Ioelovich, M. High-energy fuel pellets. *Sci. Environ.* **2020**, *3*, 147–152.
- Ioelovich, M. Recent findings and the energetic potential of plant biomass as a renewable source of biofuels—A review. *Bioresources* **2015**, *10*, 1879–1914. [\[CrossRef\]](#)
- Fahmy, T.Y.A.; Fahmy, Y.; Mobarak, F.; El-Sakhawy, M.; Abou-Zeid, R.E. Biomass pyrolysis: Past, present, and future. *Environ. Dev. Sustain.* **2020**, *22*, 17–32. [\[CrossRef\]](#)
- Dawod, A. Pyrolysis of Biomass. Master's Thesis, University of South-East Norway, Porsgrunn, Norway, 2021; p. 81.
- Tumuluru, J.S. Pelleting of pine and switchgrass blends: Effect of process variables and blend ratio on the pellet quality and energy consumption. *Energies* **2019**, *12*, 1198. [\[CrossRef\]](#)
- Ciolkosz, D.E.; Hilton, R.; Swackhamer, C.; Yi, H.; Puri, V.M.; Swomley, D.; Roth, G. Farm-scale biomass pelletizer performance for switchgrass pellet production. *Appl. Eng. Agric.* **2015**, *31*, 559–567.
- Ioelovich, M. Energy potential of natural, synthetic polymers and waste materials—A review. *Acad. J. Polym. Sci.* **2018**, *1*, 1–15. [\[CrossRef\]](#)
- McLaughlin, L.P.; Belmont, E.L. Size-resolved aerosol emissions from lignocellulosic biomass and biomass constituent pyrolysis under variable dilution temperatures. *J. Aerosol. Sci.* **2021**, *151*, 105679. [\[CrossRef\]](#)
- He, Y.; Liu, H.; Ying, W. Constructing stable polyvinyl alcohol/gelatin/cellulose nanocrystals composite electrospun membrane with excellent filtration efficiency for PM2.5. *Polymers* **2024**, *16*, 1656. [\[CrossRef\]](#)
- Larnaudie, V.; Ferrari, M.D.; Lare, C. Switchgrass as an alternative biomass for ethanol production in a biorefinery: Perspectives on technology, economics, and environmental sustainability. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112115. [\[CrossRef\]](#)
- Keshwani, D.R.; Cheng, J.J. Switchgrass for bioethanol and other value-added applications: A review. *Bioresour. Technol.* **2009**, *100*, 1515–1523. [\[CrossRef\]](#)
- Amândio, M.S.T.; Rocha, J.M.S.; Xavier, A.M.R.B. Enzymatic hydrolysis strategies for cellulosic sugars production to obtain bioethanol from eucalyptus globulus bark. *Fermentation* **2023**, *9*, 241. [\[CrossRef\]](#)
- Reis, C.E.R.; Junior, N.L.; Bento, H.B.; de Carvalho, A.K.F.; Vandenberghe, L.P.d.S.; Soccol, C.R.; Aminabhavi, T.M.; Chandel, A.K. Process strategies to reduce cellulase enzyme loading for renewable sugar production in biorefineries. *Chem. Eng. J.* **2023**, *451*, 138690. [\[CrossRef\]](#)
- Ioelovich, M. Thermodynamics of enzymatic hydrolysis of cellulose. *World J. Adv. Res. Rev.* **2024**, *21*, 577–586. [\[CrossRef\]](#)
- Da Silva, A.S.; Espinheira, R.P.; Teixeira, R.S.S.; de Souza, M.F.; Ferreira-Leitão, V.; Bon, E.P.S. Constraints and advances in high-solids enzymatic hydrolysis of lignocellulosic biomass: A critical review. *Biotechnol. Biofuels* **2020**, *13*, 58. [\[CrossRef\]](#)
- Ioelovich, M. Preparation, characterization and application of amorphized cellulose—A review. *Polymers* **2021**, *13*, 4313. [\[CrossRef\]](#)
- Xiao, Z.; Zhang, X.; Gregg, D.J.; Saddler, J.N. Effects of sugar inhibition on cellulases and beta-glucosidase during enzymatic hydrolysis of softwood substrates. *Appl. Biochem. Biotechnol.* **2004**, *113–116*, 1115–1126. [\[CrossRef\]](#)
- Ansanay, Y.; Kolar, P.; Sharma-Shivappa, R.; Cheng, J.; Arellano, C. Pretreatment of switchgrass for production of glucose via sulfonic acid-impregnated activated carbon. *Processes* **2021**, *9*, 504. [\[CrossRef\]](#)
- Mosier, N.; Wyman, C.; Dale, B.; Elander, R.; Lee, Y.Y.; Holtzapapple, M.; Ladisch, M. Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresour. Technol.* **2005**, *96*, 673–686. [\[CrossRef\]](#) [\[PubMed\]](#)
- Kumar, P.; Barrett, D.; Delwiche, M.; Stroeve, P. Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. *Ind. Eng. Chem. Res.* **2009**, *48*, 3713–3729. [\[CrossRef\]](#)
- Wyman, C.E.; Balan, V.; Dale, B.E.; Elander, R.T.; Falls, M.; Hames, B.; Holtzapapple, M.T.; Ladisch, M.R.; Lee, Y.Y.; Mosier, N.; et al. Comparative data on effects of leading pretreatments and enzyme loadings and formulations on sugar yields from different switchgrass sources. *Bioresour. Technol.* **2011**, *102*, 11052–11062. [\[CrossRef\]](#)
- Ioelovich, M. Effect of chemical pretreatments on composition and enzymatic digestibility of plant biomass. *Res. Rev. J. Chem.* **2014**, *3*, 23–31.
- Xu, H.; Che, X.; Ding, Y.; Kong, Y.; Li, B.; Tian, W. Effect of crystallinity on pretreatment and enzymatic hydrolysis of lignocellulosic biomass based on multivariate analysis. *Bioresour. Technol.* **2019**, *279*, 271–280. [\[CrossRef\]](#)

30. Zhang, H.; Han, L.; Dong, H. An insight to pretreatment, enzyme adsorption and enzymatic hydrolysis of lignocellulosic biomass: Experimental and modeling studies. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110758. [[CrossRef](#)]
31. Sluiter, J.B.; Ruiz, R.O.; Scarlata, C.J.; Sluiter, A.D.; Templeton, D.W. Compositional analysis of lignocellulosic feedstocks: Review and description of methods. *J. Agric. Food Chem.* **2010**, *58*, 9043–9053. [[CrossRef](#)]
32. Wu, J. How to make wood pellets—Small pellet mill and pellet plant. *G. Energy* **2024**, *2*, 1–5.
33. Telmo, C.; Lousada, J. Heating values of wood pellets from different species. *Biomass Bioenergy* **2011**, *35*, 2634–2639. [[CrossRef](#)]
34. Elniski, A.; Dongre, P.; Bujanovic, B.M. Lignin use in enhancing the properties of willow pellets. *Forests* **2023**, *14*, 2041. [[CrossRef](#)]

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