



Article

# Gasification of Cup Plant (*Silphium perfoliatum* L.) Biomass—Energy Recovery and Environmental Impacts

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**Abstract:** Biomass from cup plant (*Silphium perfoliatum* L.) is considered a renewable energy source that can be converted into alternative fuel. Calorific syngas, a promising type of advanced fuel, can be produced through thermochemical biomass gasification. In this study, the suitability of cup plant biomass for gasification was assessed, including the process energy balance and environmental impacts of waste from syngas purification. *Silphium perfoliatum* L. was cultivated as a gasification feedstock in different conditions (irrigation, fertilization). The experiments were performed in a membrane gasifier. All obtained energy parameters were compared to the biomass yield per hectare. The toxic effects of liquid waste were assessed using tests analyzing germination/seed root elongation of *Sinapsis alba*. Leachates collected from condensation tanks of a gas generator were introduced to soil at the following doses: 100, 1000 and 10,000 mg kg<sup>-1</sup> DM of soil. The usefulness of *Silphium perfoliatum* L. for gasification was confirmed. The factors of plant cultivation affected the biomass yield, the volume and calorific value of syngas and the amount of biochar. It was determined that the components found in condensates demonstrate a phytotoxic effect, restricting or inhibiting germination and root elongation of *Sinapsis alba*. Due to this potential hazard, the possibility of its release to the environment should be limited. Most of the biomass is only used for heating purposes, but the syngas obtained from the cup plant can be used to power cogeneration systems, which, apart from heat, also generate electricity.

**Keywords:** gasification of biomass; cup plant; bioenergy; syngas; biochar; tar; ecotoxicity

## 1. Introduction

Biomass can be transformed directly into heat or energy via thermochemical conversion processes [1]. The substrates used in these transformations include wood, agricultural and herbaceous biomass, marine biomass, human and animal waste, and contaminated and industrial waste biomass [2]. However, plant biomass, including energy crops, is the basic source of renewable energy in many countries around the world. Such crops should be characterized by high annual growth, resistance to disease and pests, low habitat requirements, and adaptation to climate conditions. *Silphium perfoliatum* L., which belongs to the *Asteraceae* family, is promising as a raw material for the production of alternative fuels [3,4].

The production of biofuels from plant biomass requires the cultivation of species with high productivity potential per unit area. An important factor in the cultivation of energy crops is the

relationship between agrotechnical activities and the amount of energy obtained. Carbon sequestration as a result of irrigation and fertilization is 0.12–3.46 and 0.32–0.74 Mg of C per 1 ha per year, respectively [5]. Fertilization and irrigation are among the treatments most affecting the productivity of plant biomass, as well as the amount of energy obtained. This is indicated by studies carried out in the cultivation of various plant species [6–9]. So far, this type of research has not been carried out in the cultivation of *Silphium perfoliatum* L., which, as a plant with a high biomass production potential and high tolerance to changing habitat conditions, may represent very interesting research material in this field. Research results on the gasification process of certain energy crops, e.g., the biomass of *Virginia mallow* L. Rusby [10] as well as miscanthus biomass, with sewage sludge [11] are promising. The addition of biomass to these energy crops resulted in increased process temperature, and thus more efficient conversion of sewage sludge to the form of syngas. Other studies conducted in the field of gasification of biomass of forest origin showed that the obtained syngas had an energy value of 4.8–5.6 MJ m<sub>N</sub><sup>-3</sup> [12].

Biomass conversion by gasification to a fuel form suitable for use in a combustion engine considerably expands its applicability [13,14]. Thermochemical processes occurring in a gas generator include combustion, pyrolysis, gasification and biomass liquefaction [15]. Biomass gasification and incineration are complex processes in physical and chemical terms, as they include issues of evaporating moisture contained in the biomass, water and tar condensation, gasification of volatile parts in the process of pyrolysis, as well as incineration on the solid/gas phase boundary and in the gas phase. The transportation of heat and mass in the packed-bed is also significant in these processes.

The biomass gasification process enables products to be obtained in which the value and the potential applicability are considerably improved in relation to the raw material [16]. It is an efficient means of conversion, yet the process itself is not without disadvantages. One of these is tar formation as an effect of incomplete biomass conversion [17]. Its presence in syngas constitutes a serious technological process and requires specific actions to be taken. Tar can be removed by optimizing gasification conditions inside the gas generator (primary methods) or after the process is completed by means of cleaning the hot gas (secondary methods) [18,19]. By means of suitable modifications to a gas generator, a portion of the hot products, including tar, can be separated from the gas stream via their cooling and condensation [20]. However, a problem arises concerning the waste obtained in this manner. The tar formed during thermochemical reactions can contain 100 different substances [21]. These include but are not limited to mixed oxygenates, phenolic ethers, alkyl phenolics, heterocyclic ethers and polycyclic aromatic hydrocarbons [17]. These water condensates can be hazardous, even at small amounts, and their presence in the environment may be linked with numerous issues.

The majority of previous studies concerning the biomass gasification process have focused on the energy balance. Environmental analyses have assessed mainly greenhouse gas emissions [22], despite liquid waste also being formed in the process. Their ecotoxicity is not fully understood, yet the available research shows that they have a negative impact on biological life, restrict the counts and activity of microorganisms significant for normal functioning of soil and demonstrate phytotoxic effects [23].

Several methods of managing the energy obtained from cup plant biomass are available. The available literature describes the methods and efficiency of obtaining biogas from the plant in the process of methane fermentation [24]. Research shows that the highest methane yield is obtained when using green cup plant biomass [25,26]. However, no articles on the thermochemical conversion of cup plant to the form of syngas can be found in available literature databases.

It has been hypothesized that *Silphium perfoliatum* L. could be used as an energy source for gasification. It has also been assumed that fertilization and irrigation influence the energy parameters and the syngas yield per hectare. Therefore, the aim of this study was to determine the amount of energy obtained from cup plant cultivated under different conditions, when subject to the gasification process in a special membrane gasifier, as well as to determine the amount of pollutants formed during its thermochemical conversion, including the phytotoxicity of liquid waste obtained from the process.

A novelty of this study is the relationship of all obtained parameters, particularly energy parameters, to the yield of cup plant obtained from one hectare. In other studies, reference is only made to kilogram of biomass or gas yield per hectare but these are not all energy parameters [25,26]. Such an assumption enables more realistic estimation of the technological process (e.g., efficiency, amount of energy and waste) and easier selection of technologies available on the biofuel market for the technical scale at the given biomass producer.

## 2. Materials and Methods

### 2.1. Material

The study material (cup plant) was cultivated at an Experimental Station in Lipnik near Stargard (53°20'36.96" N, 14°58'13.908" E) on acidic brown soil formed from clayey heap sand, good rye complex and IVb soil class. The arable layer (0–25 cm) of the soil contained 8.2 g kg<sup>-1</sup> C-organic, was slightly acidic, and possessed a low content of absorbable P forms (30.1 mg kg<sup>-1</sup>) and K (45 mg kg<sup>-1</sup>), and the groundwater level during vegetation period was below 3.0 m. The experiment was set up in a random split-block design with two factors: first-order factor—irrigation: facility W(–) without water and W(+) with water; and second-order factor—different nitrogen (N) fertilization dosages of 0 (N0), 40 (N40) and 80 kg ha<sup>-1</sup> (N80).

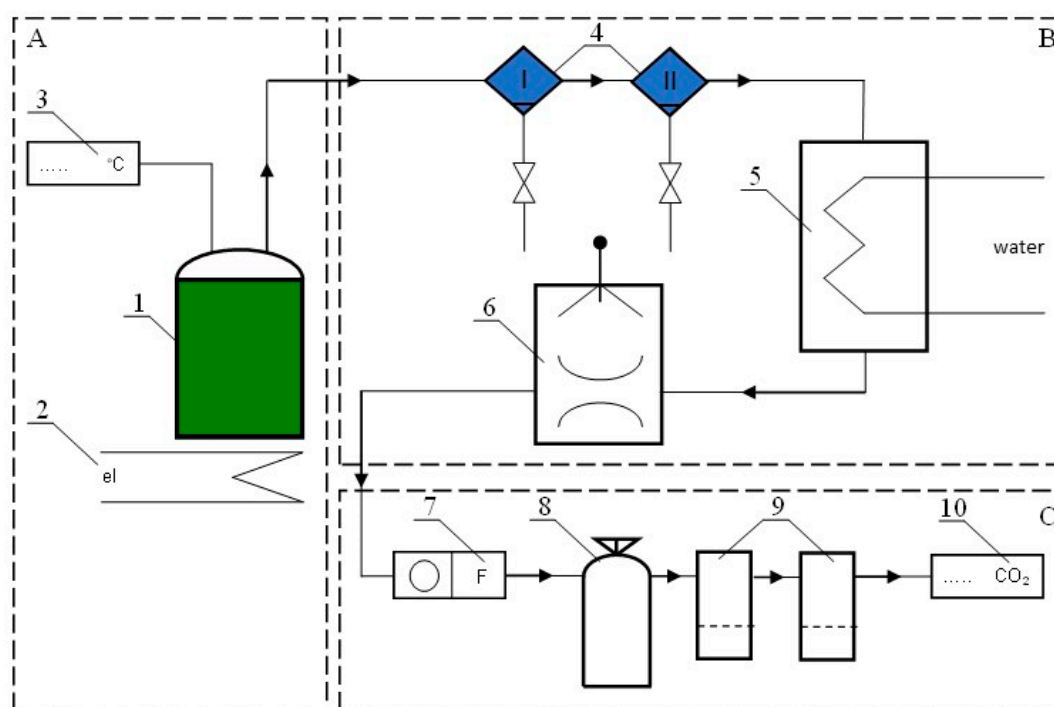
### 2.2. Experimental Setup

#### 2.2.1. Determination of the Mass and Energy Balance

In the first stage of the study, cup plant biomass humidity was determined by the dry oven test. Subsequently, the calorific value of cup plant dry biomass was tested in an IKA C 2000 calorimeter on the basis of the isoperibolic method [27]. For the calorific value tests, the test material was ground in a laboratory mill to a size below 0.2 mm.

For the gasification process, the material was prepared by disintegrating to the size of 5 mm stem length using an H122/5 type shredder (M-ROL Company, Odolanów, Poland) with a capacity of approx. 1000 kg h<sup>-1</sup> and power consumption of approx. 7.5 kW.

The model of experimental action is described schematically (Figure 1), where the arrows indicate the direction of gas flow. In the next stage of the study, a pre-pared 200 g raw material sample was placed in the chamber of a gasification reactor, used as an energy converter [28], with 3 dm<sup>3</sup> capacity, and was subject to gasification. In comparison to other gas generators, this solution is good because the syngas does not mix with the exhaust gasses prepared from partial biomass burning [29]. The gas reactor (1) was heated from an external heat source using a two-stage electric heater (2) (Selfa Company, Szczecin, Poland) included as part of the reactor (Figure 1). The heating time and the reactor operating temperature were the same for all replications. The external air access to the reactor chamber was closed. Only the air present in the reactor chamber was used during gasification. A portion of the hot, volatile products of gasification process was subject to condensation to liquid phase (water, pyrolytic oil, tars) in a two-stage water cooler (5) that was also integral to the reactor. The remaining portion of the products remaining in gas phase was directed to an MRU Vario Plus analyzer (10) in order to establish its chemical composition and (on this basis) to determine its calorific value [30]. All sample determinations were carried out in three replications.



**Figure 1.** Scheme of the test stand [28]: (A) chamber of reactor system with a fixed bed, (B) gas cleaning and cooling system and (C) measurement system for gas produced; (1) gasification reactor, (2) two-stage electric heater, (3) measure the temperature inside the reactor, (4) condensation tanks with drain valves (I and II), (5) condensate tank cooled by water, (6) scrubber (absorber), (7) gas meter, (8) tank, (9) double water filter and (10) exhaust gas analyzer.

Chemical analyses of the fuel were carried out using an MRU Vario Plus analyzer intended for continuous work, measuring emissions from all industrial incineration processes by electrochemical means and in infrared according to standard methods' [31]. After the experiment was completed, the mass of products formed as a result of gasification was determined. Subsequently, all of the obtained values were calculated with reference to one hectare of cup plant cultivation.

### 2.2.2. Seed Germination and Root Elongation Bioassay

In order to assess the ecotoxicological effect of waste from the biomass gasification process, liquid fractions accumulating in two condensation tanks (I and II) of the gasification system were used. It was assumed, among others, that different condensation temperatures in different tanks may affect the composition of liquid products and thus associated toxic effects.

Biotests were carried out, in which the level of *Sinapsis alba* seed germination level (in %) and their root growth (in mm) were assessed after 3 days' exposure to pollutants introduced to soil. In order to assess the level of contamination having a negative impact on the tested parameters, individual condensates were introduced to soil in three markedly different doses for both liquid waste from tank I, as well as tank II: 100, 1000 and 10,000 mg·kg<sup>-1</sup> dry mass (DM) of soil. The measured condensate doses were equally distributed in the soil prepared for study and were carefully mixed. Samples were left for 24 h.

Phytotoxicity tests were carried out in glass Petri dishes with 100 mm diameter. To each of the dishes, 10 g contaminated soil and 10 cm<sup>3</sup> of distilled water were added, and those dishes were covered with a filter paper. Control samples (C) only contained 5 cm<sup>3</sup> of distilled water and a filter paper. In thus-prepared Petri dishes, 10 similar-sized seeds were equally distributed on the surface of the filter paper. The test was performed in three repetitions for each test object. Closed dishes were incubated in darkness at 25 ± 1 °C. The test duration was 72 h. After the established incubation time,

the amount of germinated seeds and the length of roots was ascertained. The germination assessment only included the seeds that had a root length of over >1 mm. Based on both parameters, using the below formula [32], the germination index was also calculated (%GI) (%GI):

$$\%GI = \left( \frac{G_S \cdot L_S}{G_C \cdot L_C} \right) \cdot 100 \quad (1)$$

where  $G_S$  and  $G_C$  correspond to seed germination for the sample and control,  $L_S$  and  $L_C$  correspond to root elongation (cm) for the sample and control.

### 2.3. Statistical Analysis

Results were analyzed using the analysis of variance. The significance of differences was evaluated using Tukey's honestly significant difference test at a level of  $\alpha = 0.001$ . All the statistical analyses were carried out using a statistical software package for Windows—Dell Statistica (data analysis software system, version 13.3 (2016); Dell Inc., Tulsa, OK, USA).

## 3. Results and Discussion

### 3.1. The Mass and Energy Balance during Cup Plant Biomass Gasification Process

As a result of the conducted study, it was determined that cup plant dry weight yield increased with the increase in the level of fertilization and irrigation (Figure 2). Other cultivation studies have shown that irrigation increases yields by 50%, while fertilization does so by more than 25% [33]. The greatest yield, i.e.,  $15.12 \text{ Mg ha}^{-1}$ , was obtained for object W(+)/N80, and the difference between objects W(-)/N80 and W(+)/N80 was only 7.6%, testifying to the minor impact of irrigation on the dry weight yield at this fertilization dose.

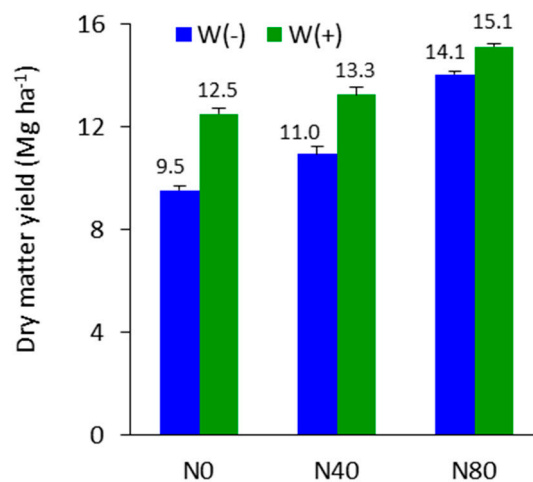


Figure 2. Cup plant dry weight yield.

A similar relationship was observed when determining calorific values of cup plant dry weight (Figure 3), where the difference between objects W(-)/N80 and W(+)/N80 was only 4.6%. As shown in Figure 3, the influence of increasing fertilizer dose was most pronounced for non-irrigated plants.

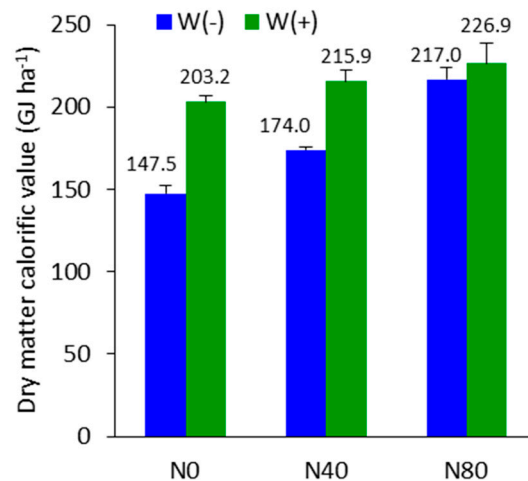


Figure 3. Calorific value of dry cup plant weight.

Volume of syngas obtained from one cultivation hectare depended strictly on cup plant yield. Due to the lack of results concerning gasification of the cup plant in the literature, the data presented in Figure 4 can only be compared with the results of the biogas production from this plant. In methane fermentation, it was a maximum of 4235 m<sub>N</sub><sup>3</sup> ha<sup>-1</sup> at the output calorific value from one hectare of 380 GJ ha<sup>-1</sup> [25,26]. In the present study, an output of 2305 m<sub>N</sub><sup>3</sup> ha<sup>-1</sup> and 227 GJ ha<sup>-1</sup> was, respectively, obtained (Figures 3 and 4). However, it should be mentioned that the amount of cup plant biomass is considerably lower for the gasification process, i.e., 10–15 Mg ha<sup>-1</sup> of dry weight as compared with 23 Mg ha<sup>-1</sup> of green cup plant mass. This fact results in a considerable reduction of costs associated with transport and additional transshipment (no need to ensilage and use additional portions of slurry).

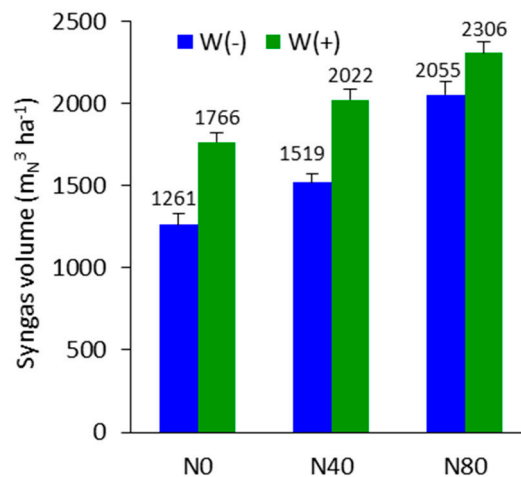


Figure 4. Volume of syngas obtained.

The results show that with irrigation of objects, the calorific value of obtained syngas calculated per cultivation surface unit is similar (the difference is only 3.7%) independently of the fertilization level (Figure 5). In the case of non-irrigated objects, increasing fertilization resulted in an increased calorific value: as much as 38.6%. The calorific value for one cubic meter of the obtained syngas was similar for all objects: 5.8–7.6 MJ m<sup>-3</sup>. Similar parameters are confirmed in the literature [12,34]. The calorific value depends on the syngas chemical composition. It was found that there was less carbon dioxide in syngas than in an ordinary gasifier and thus there was a higher calorific value [29].

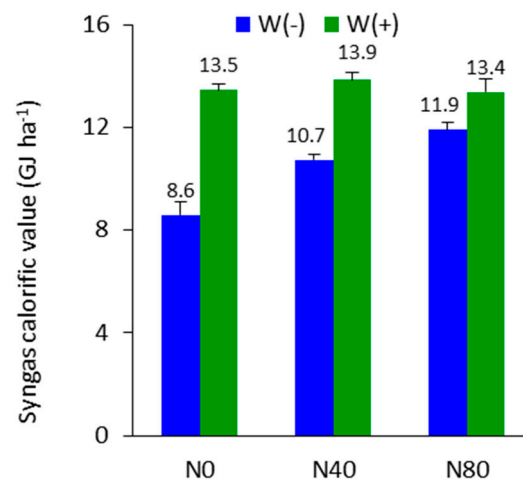


Figure 5. Calorific value of syngas obtained.

Substantial amounts of condensate were formed as a result of the gasification process (Figure 6). Converted to cultivation unit, this was an average of 4.84 Mg ha<sup>-1</sup>. It was determined that with increased fertilization and irrigation level, the amount of condensate increased by as much as 86.1% in a W(+)/N80 object in comparison with a W(-)/N0 object. A similar relationship was detected for biochar mass formed after cup plant gasification (Figure 7). However, it should be noted that the difference between W(-)/N80 and W(+)/N80 was only 4.1%, indicating the absence of any impact of irrigation on the biochar mass formed after cup plant gasification at this fertilizer dose. In this research, 32% was obtained. This was more than the average biochar content in biomass (15–20%) [35].

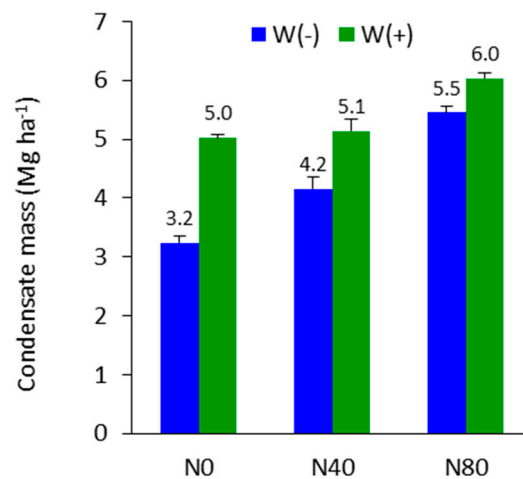


Figure 6. Mass of condensate from syngas formed.

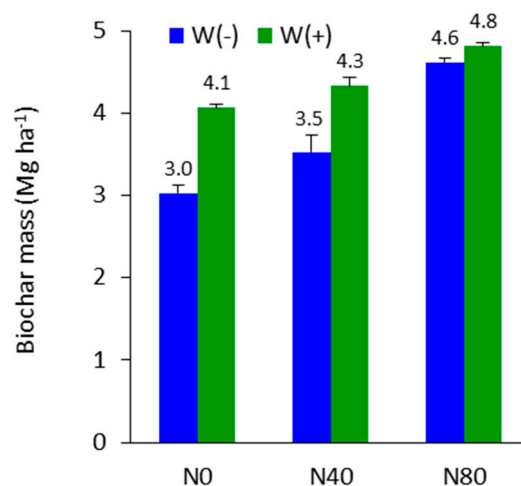


Figure 7. Biochar mass after gasification process.

A significant parameter of the conducted process of thermochemical biomass conversion is its efficiency (Figure 8). As a result of the conducted study and calculations performed, it was determined that the efficiency of the process increased slightly after plant irrigation (13.8% for N0, 3.2% for N40 and 7.3% for N80). A reduction in the process efficiency of 10.6% was also observed for a W(+)/N80 object in comparison with a W(+)/N0 object.

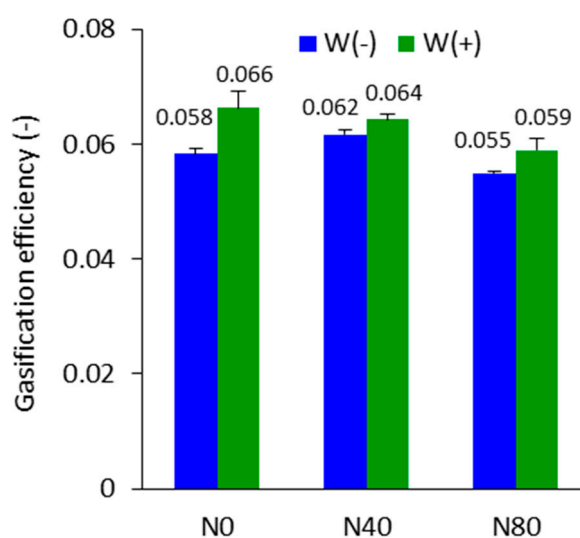


Figure 8. Gasification efficiency.

A relatively low efficiency of only 5.5–6.6% can be increased by energetic usage of the biochar produced in the process. When this factor was taken into account for the calculations, an efficiency improvement of up to 37.7% was obtained for a W(+)/N80 object (Figure 9). For the group of N0 and N40 objects, the efficiency was similar: on average 36.6%. The calculations did not include the potential calorific value of the condensate. It should be added that the gasification efficiency depends on the size and capacity of the gas generator. Increased gas generator volume favors increased efficiency of the process [36].



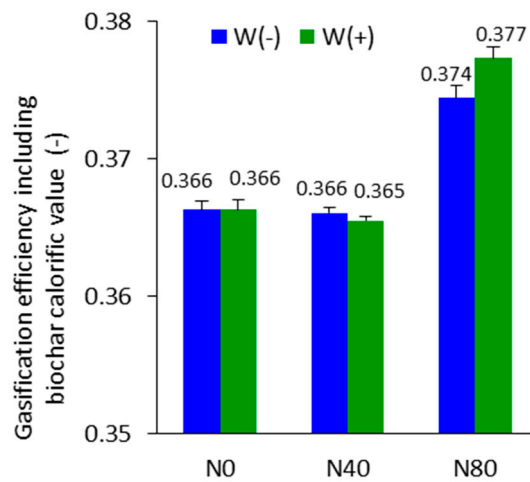


Figure 9. Process efficiency including biochar formed after gasification.

### 3.2. Phytotoxicity Tests

Based on the analysis of variance, it was established that condensate type, its dosage, the object and the interaction between these factors had a significant influence on *Sinapis alba* germination and root elongation. With increased dosage of pollution introduced to soil, the number of germinating seeds (Figure 10), as well as root length (Figure 11), decreased. Phytotoxicity in relation to both tested parameters had also been observed in earlier experiments, which analyzed the impact of pellet gasification leachates [28].

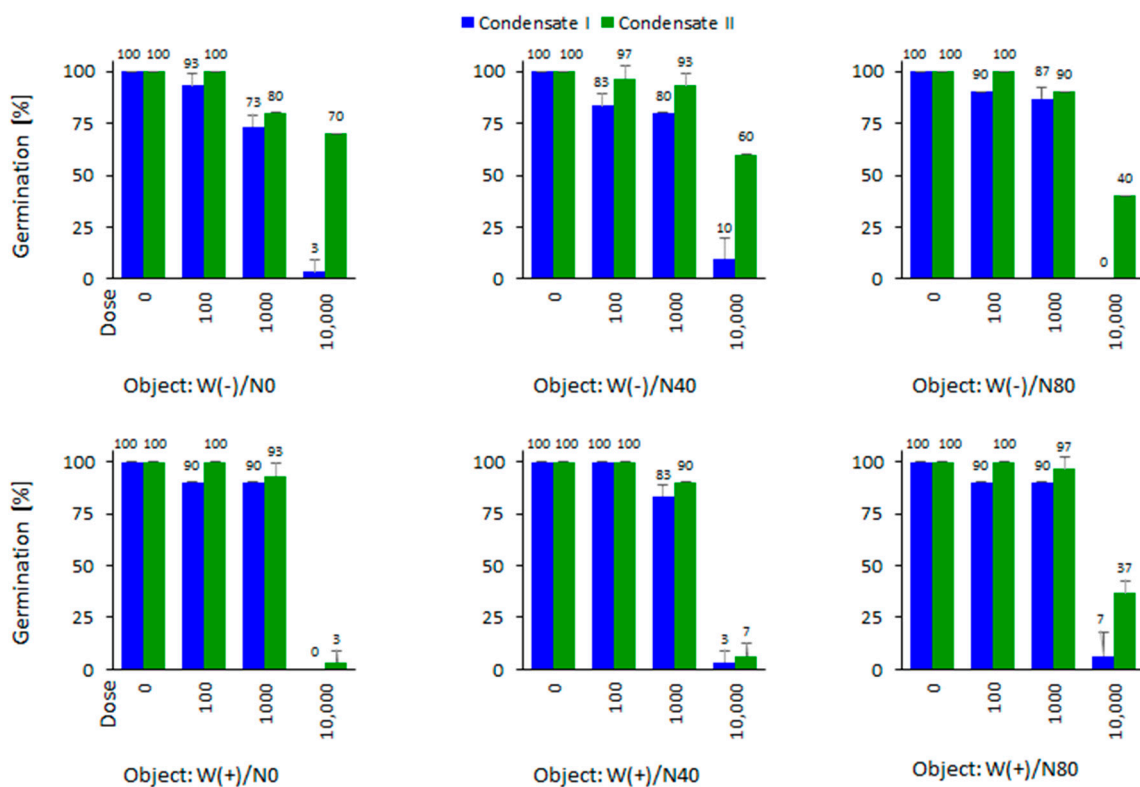
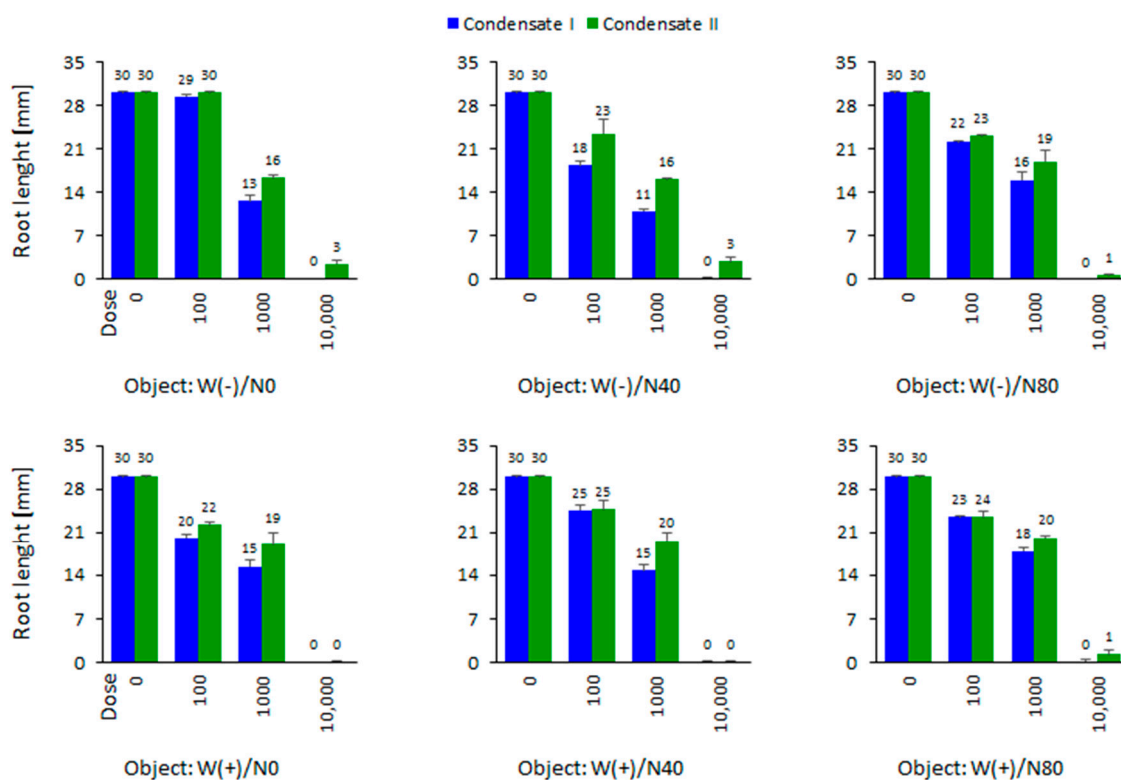


Figure 10. Effect of tar on *Sinapis alba* seed germination in ecotoxicity biotest.



**Figure 11.** Effect of tar on *Sinapis alba* root elongation in ecotoxicity biotests.

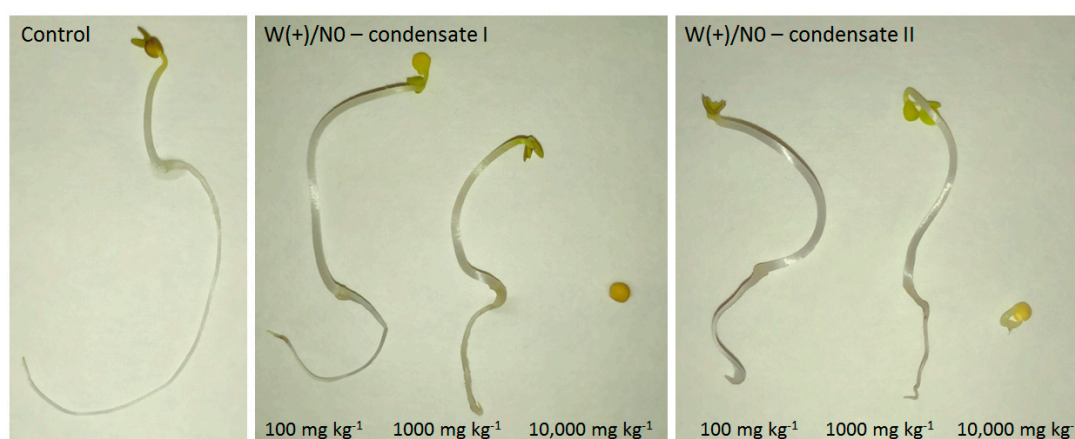
In the presented study, the number of germinating seeds was reduced in individual experimental objects in relation to the control in a range from 3–17% at the lowest dose, through 3–27% at a 10-fold dose, and up to 30–100% at the dose of 10,000 mg kg<sup>-1</sup> DM of soil. The observed changes were significantly affected by condensate type. It is likely that the majority of tar was accumulated in tank I; thus, leachates from it exhibited a more pronounced phytotoxic effect and restricted germination to a greater degree. Leachate from gasification of cup plant cultivated without irrigation, independently of the fertilization level, resulted in an increased reduction in comparison with the leachates obtained from the gasification of plants cultivated with irrigation and fertilization. Leachates obtained from individual objects probably did not differ in the proportions of chemical substances that formed their composition. Such differences without doubt occur between tars from different biomass types [37].

The presence of tar in condensates also had a negative effect on root growth. Depending on the experimental object, and in comparison with the control, reductions of 2–37% for the dose of 100 mg kg<sup>-1</sup> DM of soil, 33–63% for the dose of 1000 mg kg<sup>-1</sup> DM of soil and 90–100% for the highest dose were observed. The tar obtained during raw syngas purification contains, among others, polycyclic aromatic hydrocarbons [38], and these are primarily responsible for the toxicity of the leachate. Similarly to the germination test, in this case the leachate from W(-)/N0, W(-)/N40 and W(-)/N80, objects also had a more pronounced negative impact on root elongation. The negative impact of PAHs, including those found in carbon tar, was also observed by Smith et al. [39], who examined seven grass and legume species and recorded reduced growth and development of test plants.

Analysis of the germination index further confirmed the observed regularities. Reduction of the value of this index with increased pollution dose was observed, independently of condensate type (Table 1). The performed ecotoxicity tests confirmed the negative effect of the presence in soil of leachates from the gasification process (Figure 12). Results of studies conducted by Chidikofan et al. [37] not only confirmed the environmental risk associated with introducing such liquid waste to environment, they also showed that negative effects of discharge to water are even stronger than those for soil.

**Table 1.** Germination index in particular test objects depending on condensate type and dose.

Condensate	Dose [mg kg <sup>-1</sup> ]	Germination Index [%GI]					
		W(-)/N0	W(-)/N40	W(-)/N80	W(+)/N0	W(+)/N40	W(+)/N80
I	0	100	100	100	100	100	100
	100	90	50	66	60	83	69
	1000	32	29	48	46	40	54
	10,000	0	0	0	0	0	0
II	0	100	100	100	100	100	100
	100	100	74	77	74	83	80
	1000	44	50	55	59	60	65
	10,000	6	6	1	0	0	2

**Figure 12.** Phytotoxic effect of condensate components I and II on seed germination and root elongation in W(+)/N0 object in relation to control.

#### 4. Conclusions

The results confirmed the possibility of using *Silphium perfoliatum* L. for thermochemical conversion to syngas. Based on these results, the technological parameters necessary to select the gasification system can be estimated.

Irrigation and fertilization increased the biomass yield. These had a positive effect on the analyzed energy parameters. There was an increase in the calorific value of biomass and the volume of syngas obtained per hectare. The calorific value of syngas increased due to fertilization. Irrigation and fertilization increased the amount of biochar per hectare, but did not affect the efficiency of the gasification process.

Under the conditions of the research, the irrigation of the fertilized plants did not affect the energy parameters of the obtained syngas. Despite the low efficiency of the gasification process, it is a favorable situation to use syngas to supply cogeneration systems, where power is produced alongside heat.

Selection of the gasification process, followed by condensate separation from the formed syngas, contributes to reduced environmental pollution, because during biomass incineration the products penetrate to the atmosphere with flue gas. The results showed that liquid wastes formed in the cup plant biomass gasification process exhibit phytotoxic effects. Biotests showed that the plant cultivation method and the introduced pollution dose had significant impacts on the observed changes. Syngas purification from tar improves its quality; yet, at the same time it results in leachate production, which should be suitably neutralized. The possible presence of this type of pollution would require suitable remediation activities to be undertaken.

**Author Contributions:** A.K., M.H.-P. and C.P. designed the study. A.K., M.H.-P., C.P., P.S. and E.M. carried out the experiments. A.K. and M.H.-P. helped to discuss and analyze the data. All authors contributed to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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