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BIOMASS AND BIOGAS PRODUCTIVITY FROM PERENNIAL HERBACEOUS CROPS AS AN ENVIRONMENTALLY FRIENDLY SOURCE OF ENERGY

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under the supervision of
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Wydajność biomasy i biogazu z bylin wieloletnich jako przyjazne dla środowiska źródło energii

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Contents

1. Summary 4

2. Streszczenie 5

3. List of publications making up the doctoral dissertation 6

4. Introduction 7

5. The aim of the study 9

6. Materials and methods 10

Field experiment 10

Laboratory experiment 12

Statistical analysis 14

7. Results and discussion 15

Meteorological data 15

7.1. Plants development and green biomass quality of *Helianthus salicifolius* and *Silphium perfoliatum* 16

7.2. Biomass and silage of *Helianthus salicifolius* as a feedstock for biogas production 18

7.3. Biomass and silage of *Silphium perfoliatum* as a feedstock for biogas production 20

7.4. The biomass yield, biogas and energy potential of *Silphium perfoliatum* and *Helianthus salicifolius* 24

8. Conclusions 28

Acknowledgments 29

References 30

1. Summary

Renewable energy is becoming a widely debated topic, identify different biomass sources that are acceptable for biomass production, easy to grow, cheap and offers high yields that will be suitable for energy feedstock, that is the subject of many researchers. This doctoral thesis contains the results of field research and laboratory analysis of perennial herbaceous crops (PHC), including cup plant (*Silphium perfoliatum* L.) and willow–leaf sunflower (*Helianthus salicifolius* A. Dietr). Research was conducted at the Department of Genetics, Plant Breeding and Bioresource Engineering and Department of Environmental Engineering, University of Warmia and Mazury in Olsztyn, Poland. *Silphium perfoliatum* and *Helianthus salicifolius* are from the Asteraceae family, native to North America and both are semi-woody perennial crops. The aim of the research was to assess the yield and quality of biomass as well biogas potential and economic analysis of PHC species depending on the fertilization type and doses of nitrogen which was applied. Determination of biomass yield/quality and other selected parameters were determined by cutting whole plants manually every year in September. Moreover, measurements on biomass quality, chemical composition and biogas properties of PHC species were studied. In addition, the most recent literature in the researched field was analyzed to compare the obtained results.

Based on obtained results, the three-year mean dry matter yield (8.0 Mg ha^{-1} y^{-1} DM) of *Silphium perfoliatum* was significantly higher compared to the *Helianthus salicifolius* by 16.3%. The highest biomass yield of *Silphium perfoliatum* (16.3 Mg ha^{-1} y^{-1} DM) was obtained in 2021 with mineral fertilization at 170 kg ha^{-1} N. As well, it can be concluded that application of different forms of fertilization (organic, mineral) and N fertilization level (85 and 170 kg ha^{-1} N) significantly influenced most of the chemical and thermophysical features. The present thesis clearly shows that biogas, methane and energy potential yield of *Silphium perfoliatum* was higher, compared to the *Helianthus salicifolius* biomass.

The obtained results allowed to supplement the knowledge on the use of *Silphium perfoliatum* and *Helianthus salicifolius* as a source of green renewable energy and offers a wide information about their features and characteristics based on complex analyzes made in this research. This PhD thesis is a collection of four papers describing the experiments carried out during the research period. The detailed information can be found at published papers in very good JCR Journals as: Industrial Crops and Products (1), Energies (2) and Energy (1).

Keywords: *Silphium perfoliatum*, *Helianthus salicifolius*, fertilization, biomass, biomass characteristics, anaerobic digestion, silage, biogas, biomethane, yield energy value

2. Streszczenie

Energia odnawialna staje się szeroko dyskutowanym tematem przez wielu badaczy. Identyfikuje się różne źródła biomasy, akceptowalne do produkcji, łatwe w uprawie, tanie i oferujące wysokie plony, które będą odpowiednie jako surowce energetyczne. Praca doktorska zawiera wyniki badań terenowych i analiz laboratoryjnych dwóch gatunków wieloletnich roślin zielnych (PHC), w tym rożnika przerośniętego (*Silphium perfoliatum* L.) i słonecznika wierzbolistnego (*Helianthus salicifolius* A. Dietr). Badania przeprowadzono w Katedrze Genetyki, Hodowli Roślin i Inżynierii Biosurowców oraz w Katedrze Inżynierii Środowiska, Uniwersytetu Warmińsko-Mazurskiego w Olsztynie. *Silphium perfoliatum* i *Helianthus salicifolius* pochodzą z rodziny Asteraceae, z Ameryki Północnej i oba są półzdrewniałymi roślinami wieloletnimi.

Celem badań była ocena plonowania, jakości biomasy oraz potencjału biogazowego i analiza ekonomiczna dwóch gatunków PHC w zależności od rodzaju nawożenia i zastosowanych dawek azotu. Oznaczanie plonu/jakości biomasy oraz inne wybrane parametry określano poprzez ręczne ścinanie całych roślin co roku we wrześniu. Ponadto przeprowadzono pomiary jakości biomasy, składu chemicznego i właściwości biogazu z biomasy gatunków PHC. Dodatkowo przeanalizowano najnowszą literaturę z badanej dziedziny w celu porównania uzyskanych wyników.

Na podstawie uzyskanych wyników stwierdzono, że średni trzyletni plon suchej masy (8,0 Mg ha^{-1} rok^{-1} s.m.) *Silphium perfoliatum* był istotnie wyższy o 16,3% w porównaniu z *Helianthus salicifolius*. Najwyższy plon biomasy uzyskano w wariancie uprawy *Silphium perfoliatum* (16,3 Mg ha^{-1} rok^{-1} s.m.) w 2021 r. przy nawożeniu mineralnym na poziomie 170 kg ha^{-1} N. Stwierdzono również, że stosowanie różnych form nawożenia (organiczne, mineralne) oraz poziom nawożenia N (85 i 170 kg ha^{-1} N) istotnie wpływały na większość cech chemicznych i termofizycznych pozyskanej biomasy. Z przedstawionej pracy jasno wynika, że plon biogazu, metanu i potencjału energetycznego *Silphium perfoliatum* był wyższy w porównaniu z *Helianthus salicifolius*.

Uzyskane wyniki pozwoliły uzupełnić wiedzę na temat wykorzystania *Silphium perfoliatum* i *Helianthus salicifolius* jako źródła zielonej energii odnawialnej oraz oferują szeroką informację o ich cechach i właściwościach na podstawie kompleksowych analiz wykonanych w niniejszych badaniach. Niniejsza praca doktorska jest zbiorem czterech artykułów opisujących eksperymenty przeprowadzone w okresie badawczym. Szczegółowe informacje można znaleźć w artykułach opublikowanych w bardzo dobrych czasopismach JCR, takich jak: Industrial Crops and Products (1), Energies (2) i Energy (1).

Słowa kluczowe: *Silphium perfoliatum, Helianthus salicifolius,* nawożenie, biomasa, charakterystyka biomasy, fermentacja beztlenowa, kiszonka, biogaz, biometan, wartość energetyczna plonu

3. List of publications making up the doctoral dissertation

1. **Peni D.,** Stolarski M.J., Dębowski M. Green biomass quality of perennial her-baceous crops depending on the species, type and level of fertilization. Industrial Crops and Products 2022, 184, 115026. https://doi.org/10.1016/j.indcrop.2022.115026. (**IF=6.449; 200 points**).

2. **Peni D.,** Dębowski M., Stolarski M.J. *Helianthus salicifolius* as a New Biomass Source for Biogas Production. Energies 2022, 15, 2921. https://doi.org/10.3390/en15082921. (**IF=3.252; 140 points**).

3. **Peni D.,** Dębowski M., Stolarski M.J. Influence of the Fertilization Method on the *Silphium perfoliatum* Biomass Composition and Methane Fermentation Efficiency. Energies 2022, 15, 927. https://doi.org/10.3390/en15030927. (**IF=3.252; 140 points**).

4. Stolarski M.J., **Peni D.,** Dębowski M. Biogas potential of cup plant and willow-leaf sunflower biomass. Energy 2022, 255, 124559; https://doi.org/10.1016/j.energy.2022.124559. (**IF=8.857; 200 points**).

4. Introduction

In the last decades of the 20th century, non-renewable energy sources (fossil fuels) are having a huge impact on the economic and technological development and remaining the most important source of energy used worldwide. Since of the negative effects on widespread, one of the objectives of the Bioeconomy Strategy for EU comes to reduce energy dependence on non-renewable and unsustainable sources [1]. Counteracting environmental degradation and climate change is a priority in energy policy in EU. The energy policy to counteract the negative effects, the newly introduced European Climate Law [2], all of this to reduce greenhouse gases for neutral economy to become climate-neutral by 2050 (European Green Deal) [3]. Unfortunately, recent geopolitical developments have accentuated the problems of dependence on fossil energy or raw materials and lack of alternative energy. The need to replace fossil fuels with renewable energy sources is a pressing urgency in the current conditions. Therefore, increasing share of renewable energy source (as well from agricultural waste and cultivated energy crops) plays a pivotal role in the concept of sustainability, circular, and zero-emission economy. The importance of sustainable agriculture and the use of locally available resources should become more and more important. Biomass, represent high energy potential in renewable energy resources sector and researchers are trying to identify suitable sources of feedstock for renewable energy. Biomass is plant-based material, which is considered to be an organic, non-fossil, used to produce renewable energy including biogas production. Biogas is a product of the microbial degradation of organic matter under anaerobic conditions. Anaerobic digestion (AD) is a biological process and great method of converting organic matter into green fuel/methane [4, 5], as well perennial herbaceous crops (PHCs) are promising feedstock for renewable energy technologies [6], decrease the greenhouse gas emissions and other benefits for biodiversity [7, 8]. In the current PhD thesis, two PHCs, including cup plant (*Silphium perfoliatum* L.) and willow–leaf sunflower (*Helianthus salicifolius* A. Dietr), were investigated their potential as a feedstock for renewable energy purposes such as biogas production.

Silphium perfoliatum is a crop from genus of the sunflower family (*Asteraceae*), part of *Heliantheae* which comes from North America [9]. *Silphium perfoliatum* field does not require recultivation for 20 years, resulting in soil protection. Its fields contribute to the improving biodiversity being considered an advantage also for the pollinators and honey producing insects [10]. Other advantages of using a field for longer periods include reduced expenses on pesticides or herbicides due to shadow created by leaves, excluding first year of growth [11].

Nowadays, *Silphium perfoliatum* is seen as a promising substrate for biogas production. It is resistant to low drained soils and on frost temperatures, being also possibly to plant it on marginal or polluted soils due to its [11, 12].

Helianthus salicifolius A. Dietr (willow-leaf sunflower) is a semi-woody plant that has low soil or climatic requirements, being resistant to drought, pests and frost [13]. It is native to North America, especially dry territories of the central US [14]. Furthermore, *Helianthus salicifolius* grows up to 2.5–3.5 m in height, producing numerous shoots. It's color is light green to purple red. It produces small, yellow flowers, similar in their structure with the common sunflower. The *Helianthus salicifolius* plant represents high interest due to it's potential to be used as energy feedstock.

The investigations carried out during the four years research activity allowed to partially cover the gap of knowledge about biomass and biogas potential of the selected PHC species, as well their characteristics (such as thermophysical and chemical properties). I believe that by investigating these crops as energy crops, present dissertation contributed to the innovation of agricultural production with multiple benefits for the environment, economy, and biodiversity.

5. The aim of the study

Therefore, the aim of the PhD dissertation was:

- Evaluation of plants development of *Silphium perfoliatum* and *Helianthus salicifolius* for three years field experiment.
- Evaluation of thermophysical and chemical properties of green biomass of *Silphium perfoliatum* and *Helianthus salicifolius* species treated with two different fertilizers applied in three different doses.
- Estimation the effect of feedstock type such as raw biomass and silage on anaerobic digestion.
- Verification of the influence of fertilization type and N dose on the biomass composition and efficiency of biogas production and methane content.
- Evaluation of the effectiveness of anaerobic digestion of *Silphium perfoliatum* and *Helianthus salicifolius* depending on PHC species, type and level of fertilization and cultivation years.
- Determination of dry matter yield, biogas, and methane potential yield depending on PHC species, type and level of fertilization and the harvest year.
- Economic analysis of biomass production and energy potential yield.

6. Materials and methods

Field experiment

A field experiment was carried out on land owned by the Research Station of the University of Warmia and Mazury in Olsztyn (UWM) in the north-east of Poland (53°59′ N, 21°09′ E). The experiment involved an analyze of the potential for biomass and biogas productivity from selected PHC species and was carried out from 2013 and 2017, but the study presented in this thesis is based on the three consecutive year 2019, 2020, 2021.

The presented study was based on two different crops (*Silphium perfoliatum* and *Helianthus salicifolius*) at the same location with the adjacent plots on 20 m^2. Experiment was established on a 4^{th} grade soil site. The organic matter content on soil in the humic horizon (0–25 cm) was 2.91%, and its pH (KCl) was 6.27%. In the experimental plots were applied different doses of mineral and organics fertilization and control plots without fertilization. In the study were involved two nitrogen (N) fertilization levels: 85 and 170 kg ha^{-1} N for each fertilization form (mineral and organic). Each experiment plot was run in three replicates. No chemical plant protection products were applied during the experiment. The *Helianthus salicifolius* plantations (Figure 1) were planted in 2013 at an initial density of 20 thousand ha^{-1}. Since that year the harvest were made every year. However, the data for this dissertation was investigated the harvests from years 2019 to 2021, thus the seventh, eighth and ninth vegetation season. The *Silphium perfoliatum* plantation (Figure 2) was planted in 2017 at an initial density of 10 thousand ha^{-1}. So, the harvested material for this study was from 2019 to 2021, consequently the third, fourth and fifth vegetation season. Therefore, monthly growth dynamics, phenological observations during the growing season was determined for both species on each plot. Moreover, the diameter, height of the shoot of the plants and plant density, as well determining the amount of fresh weight from each plot were carried out after the end of the growing season (Figure 3-6).



Figure 1. *Helianthus salicifolius* plantations.



Figure 2. *Silphium perfoliatum* plants



Figure 3. Measurments of *Silphium perfoliatum* plantations in July 2019.



Figure 4. Harvesting *Helianthus salicifolius* plantations in September 2021.



Figure 5. Harvesting *Silphium perfoliatum* plantations in September 2021.



Figure 6. Weighing fresh biomass of *Helianthus salicifolius* after harvesting.

Laboratory experiment

During the 2019 to 2021 years the experimental isolated samples of PHCs were also investigated on other features related to the energy characteristics, such as: moisture content, fixed carbon content, volatile matter content, higher heating value, ash content, hydrogen content, carbon content, sulfur content, total nitrogen content, chlorine content, the content of compounds soluble in cold water, the content of compounds soluble in hot water, other soluble substances, hemicellulose content, cellulose content and lignin content. All these analyses were performed in the laboratory of Department of Genetics, Plant Breeding and Bioresource Engineering at UWM.

In laboratory at Department of Environmental Engineering were performed measurements related with biogas and methane production. The measurements were performed from raw and ensilaged biomass (silage). The silage was obtained by ensiling raw fresh biomass of crops immediately after harvesting directly in plastic silos. All samples were dried using a FD BINDER laboratory dryer (Tuttling, Germany) and milled in a Retsch SM 200 cutting mill (Haan, Germany) using a 1 mm sieve to prepare the material for analyses. An IKA C2000 calorimeter (Staufen, Germany) was used to determine the higher heating value based on the dynamic method, and automatic ELTRA CHS–500 analyzer (Neuss, Germany) (Figure 7) was used to determine the carbon, hydrogen, and sulfur contents according to the PN–EN ISO 16948:2015–07 and 16994:2016–10 standards. The automatic ELTRA TGA–THERMOSTEP analyzer (Neuss, Germany) (Figure 8) was used to determine the volatile matter and ash contents according to the PN–EN ISO 18122:2016–01 and PN–EN ISO 18123:2016–01 standards.

To determine chlorine content by calcination of the samples at the temperature of 650 °C in the presence of the K2S and MgO mixture was used a Nabertherm muffle furnace (Lilienthal, Germany), and the aqueous extract of the sample was titrated with 0.025 mol/L AgNO3 according to the PN–EN ISO 587:2000 standard.

The biomethane generation were performed on laboratory scale in 500 cm^3 reactors coupled with the change registration system in partial pressure using Automatic Methane Potential Test System II (AMPTS II) (BPC Instruments AB, Lund, Sweden) (Figure 9). The composition of biogas was measured using the gas chromatograph (Figure 10) connected to a thermal conductivity detector (TCD) (GC Agilent 7890 A–Agilent Technologies, Santa Clara, with argon (Ar) and helium (He) as the carrier gases.

The purpose of this section was only to provide the reader with general information that was used in this doctoral dissertation. All detailed information on the measurements, analyzed features and experimental techniques used to perform the experiments have been described in the relevant publications on which this doctoral thesis is based.



Figure 7. Automatic ELTRA CHS–500 analyzer.



Figure 8. Automatic ELTRA TGA–THERMOSTEP analyzer.



Figure 9. Automatic Methane Potential Test System II.



Figure 10. Gas chromatograph GC Agilent 7890 A–Agilent Technologies.

Statistical analysis

The genotype (factor A), fertilization type (factor B) and the level of nitrogen fertilization (C) were the fixed and grouping factors in this analysis and the three consecutive harvest years (2019, 2020, 2021) were the repeated measures factor (D). The Shapiro-Wilk test was applied to verify the normality of the attributes under study. The statistical analysis of the attributes under study was based on Repeated Measures ANOVA. Additionally, a three-factorial analysis of variance for the sums of dry matter yield, biogas and methane potential yield, potential energy yield from three consecutive years (2019-2021) was performed for the three main study factors (A, B, C).

The arithmetic mean and the standard deviation were calculated for each of the analyzed attributes. Homogeneous groups were identified with Tukey's honestly significant difference (HSD) test at the level of significance of $P < 0.05$. Additionally, agglomerative hierarchical clustering analysis was performed for the determined biomass parameters of the studied PHC species. All statistical analyses were conducted with STATISTICA 13 (TIBCO Software Inc.).

7. Results and discussion

Meteorological data

The meteorological data during the three years experiment (2019-2021) and the average for several years were presented in Figure 11 (based on data registered by meteorological station located in Łężany). The mean of annual temperature for investigated period ranged from 7.4 to 9.8 °C. The highest mean monthly air temperature (20.8 °C) was noted in June 2019, and it was 3.9 ◦C higher as compared with the values from the multi-year average (1988–2021). The highest mean of precipitation was in 2020, which was 567 mm, but it was significantly lower than the multi-year average which was 682 mm.

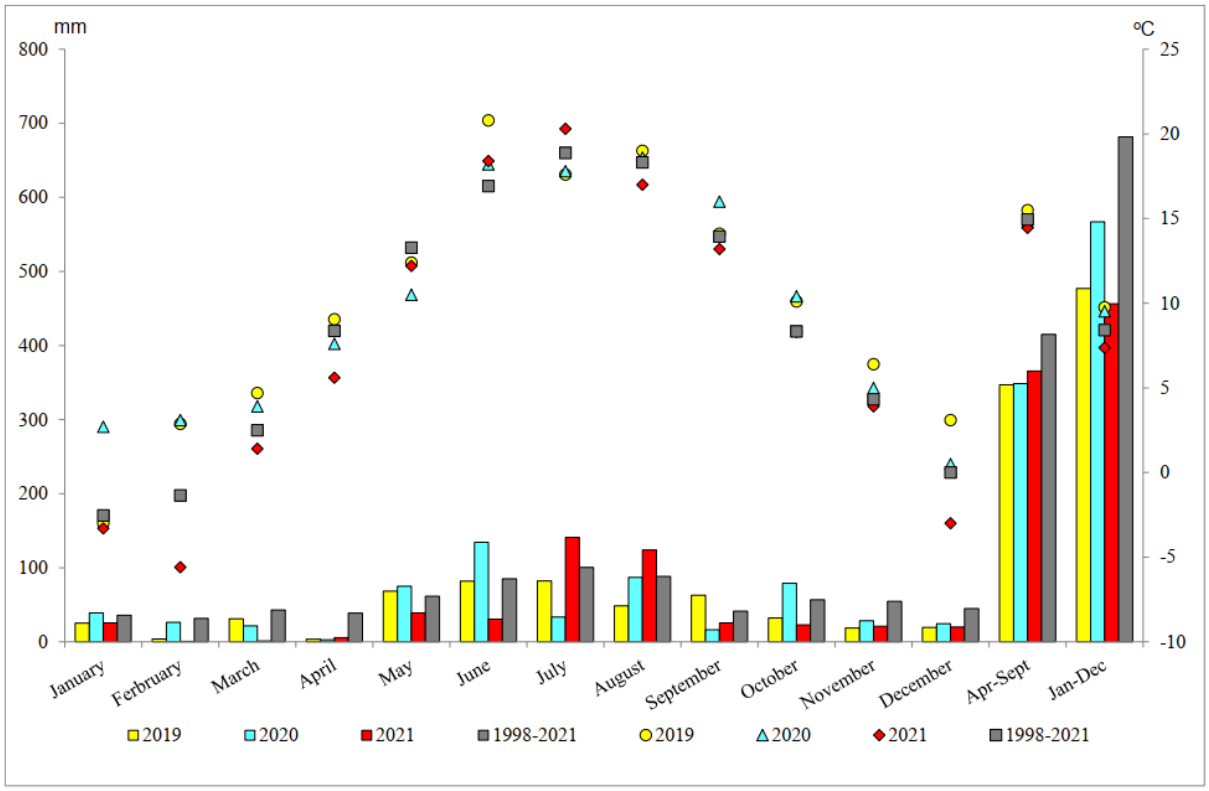


Figure 11. Weather conditions during the experiment (2019-2021) and multi-year period (1998-2021). Bars represent precipitation; geometric figures represent air temperatures.

7.1. Plants development and green biomass quality of *Helianthus salicifolius* and *Silphium perfoliatum*

The plants development, biomass characteristic and chemical composition of two PHC species, *Silphium perfoliatum* and *Helianthus salicifolius*, were investigated depending on the type and level of fertilization, during the three-year trials. The number of shoots per 1 m^2, diameter and height varied significantly between different species and fertilization type, where the nitrogen level significantly influenced only height of plants. *Helianthus salicifolius* produced, on average, over four times more shoots per 1 m^2 than *Silphium perfoliatum*. However, the *Helianthus salicifolius* shoots, on average, were lower by over 70 cm and more than two times smaller diameter (Figure 12).

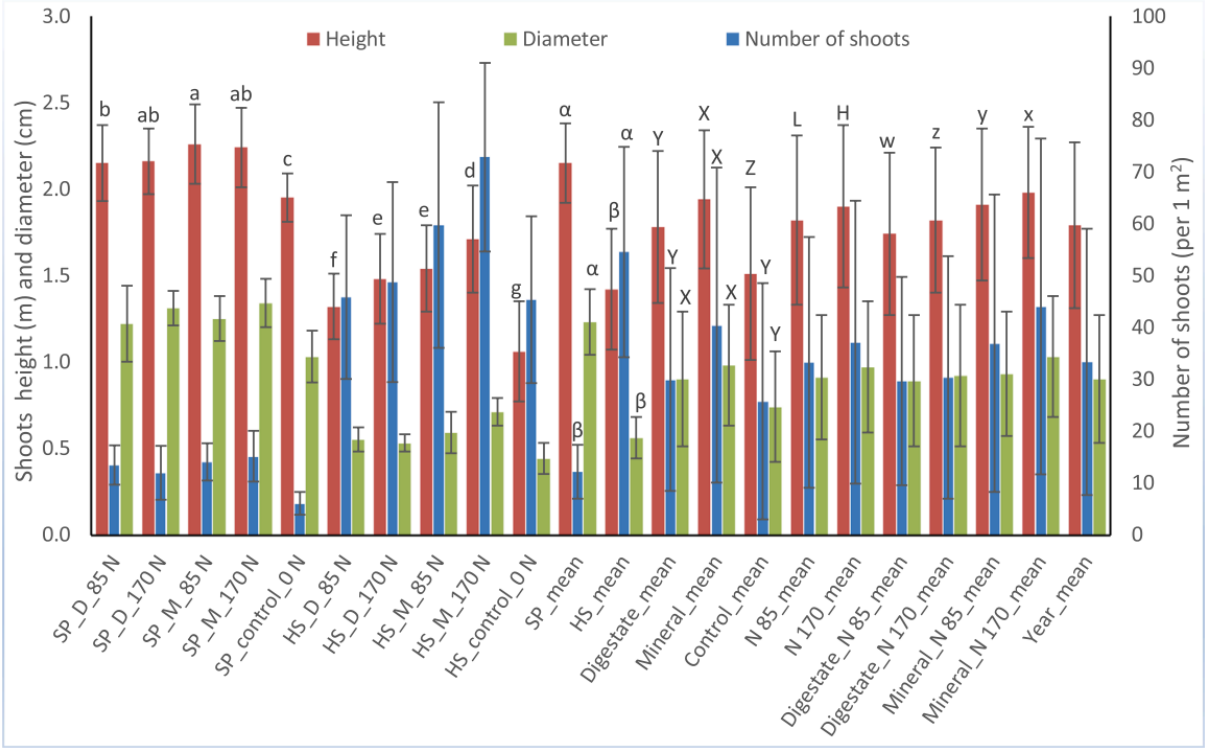


Figure 12. Mean values for three experimental years (2019–2021) for the number of shoots and the shoot height and diameter, depending on the PHC species, type, and doses of fertilization. The bars denote the standard deviation.

The application of organic and mineral fertilization resulted in a decrease in moisture, ash and lignin contents. significantly influenced most of the features of investigated biomass such as chlorine, cellulose and hemicellulose content, and slightly increased the higher heating value and significantly increased the chlorine, hemicellulose and cellulose content. Moreover, application of the nitrogen dose of 170 kg ha^{-1} slightly increased the moisture, higher heating value, volatile matter, carbon, hydrogen, sulfur, total nitrogen, chlorine, hemicellulose and cellulose content. Therefore, *Silphium perfoliatum* biomass was characterized by higher contents of moisture content, ash content chlorine content, lignin and cellulose. The mean moisture content of green *Silphium perfoliatum* biomass (75.8%) was 14.8% higher than in the case of *Helianthus salicifolius*. Results found in the literature for *Silphium perfoliatum* harvested for biogas purposes and forage purposes, indicated that the moisture content was similar as in present study and ranged from 70.0% to 79.0% [15]. Recent study presents a very high moisture content (79.1%) in the *Helianthus salicifolius* biomass harvested in June [16] compared with this study obtained data. Also, the literature provides similar data on the ash content in *Silphium perfoliatum* biomass, ranging from 8.0% to 9.4% DM, for crops harvested in August, October and in December [17-19]. The ash content in the biomass of this species was also influenced by the method of plantation establishment, either by sowing or planting, and was 4.1% and 3.1% DM, respectively, for the biomass harvested in January [20]. Another recent study provided in Poland presented that harvesting period plays an important role in the ash content in different structural parts of *Silphium perfoliatum* [21]. On the other hand, *Helianthus salicifolius* biomass contained more carbon content, fixed carbon content, hydrogen content, sulfur content, higher heating value and hemicellulose. All detailed analyzed features for whole experiment were presented in the supplementary data (Tables S1-S19).

7.2. Biomass and silage of *Helianthus salicifolius* as a feedstock for biogas production

The biomass composition, biomethane and biogas potential of *Helianthus salicifolius* were investigated, as a new and unused substrate in biogas production technologies. The research was provided on both, raw green biomass and silage of *Helianthus salicifolius*, under different type of fertilization and doses. The characteristics of silage and raw material of *Helianthus salicifolius* used for the preparation of feedstock for biogas production is presented in Figure 13. The biogas production was calculated/reported after 25-day period under anaerobic digestion. Moreover, daily biogas and biomethane production outputs from silages and raw substrates from *Helianthus salicifolius* are presented in Figure 14. The amount of biomethane production was measured by respirometric tests, the measurement system recorded changes in partial pressure supplemented with reactors.

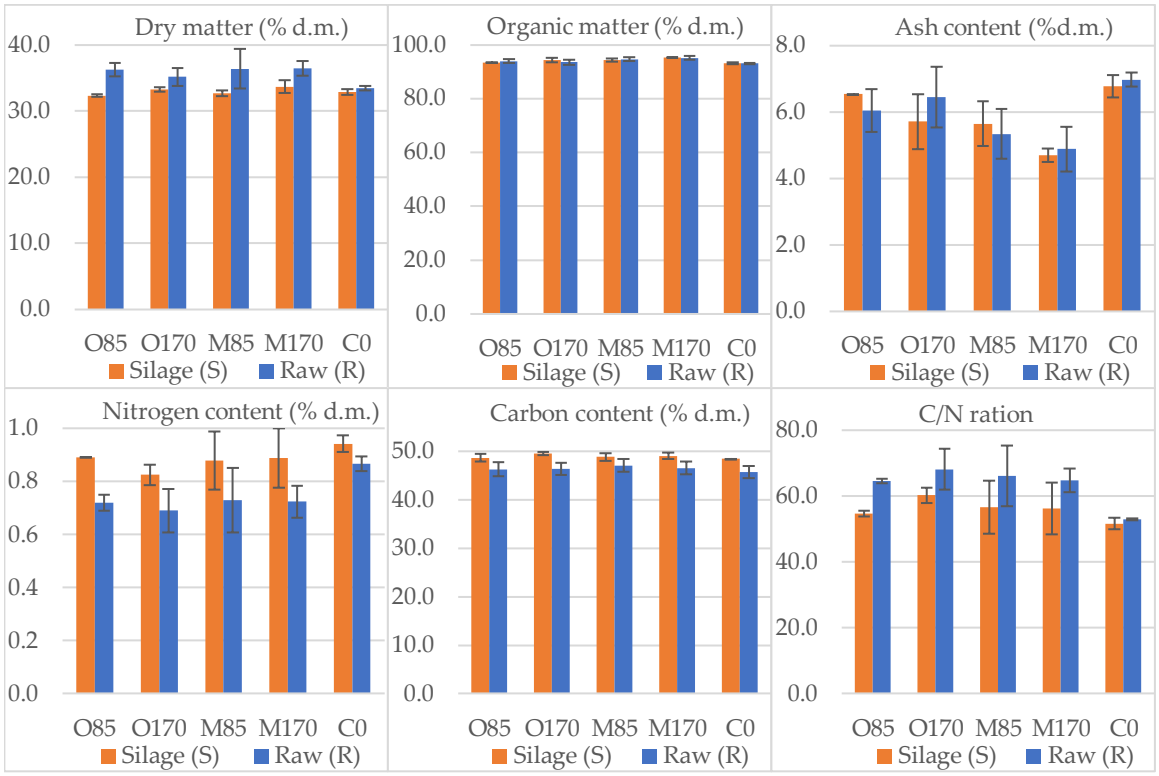


Figure 13. Characteristics of silage and raw material of *Helianthus salicifolius* used for the preparation of feedstock. (C0 – without fertilization; M85 – mineral fertilization 85 kg N ha^{-1}; M170 – mineral fertilization 170 kg N ha^{-1}; O85 – organic fertilization 85 kg N ha^{-1}; O170 – organic fertilization 170 kg N ha^{-1}).

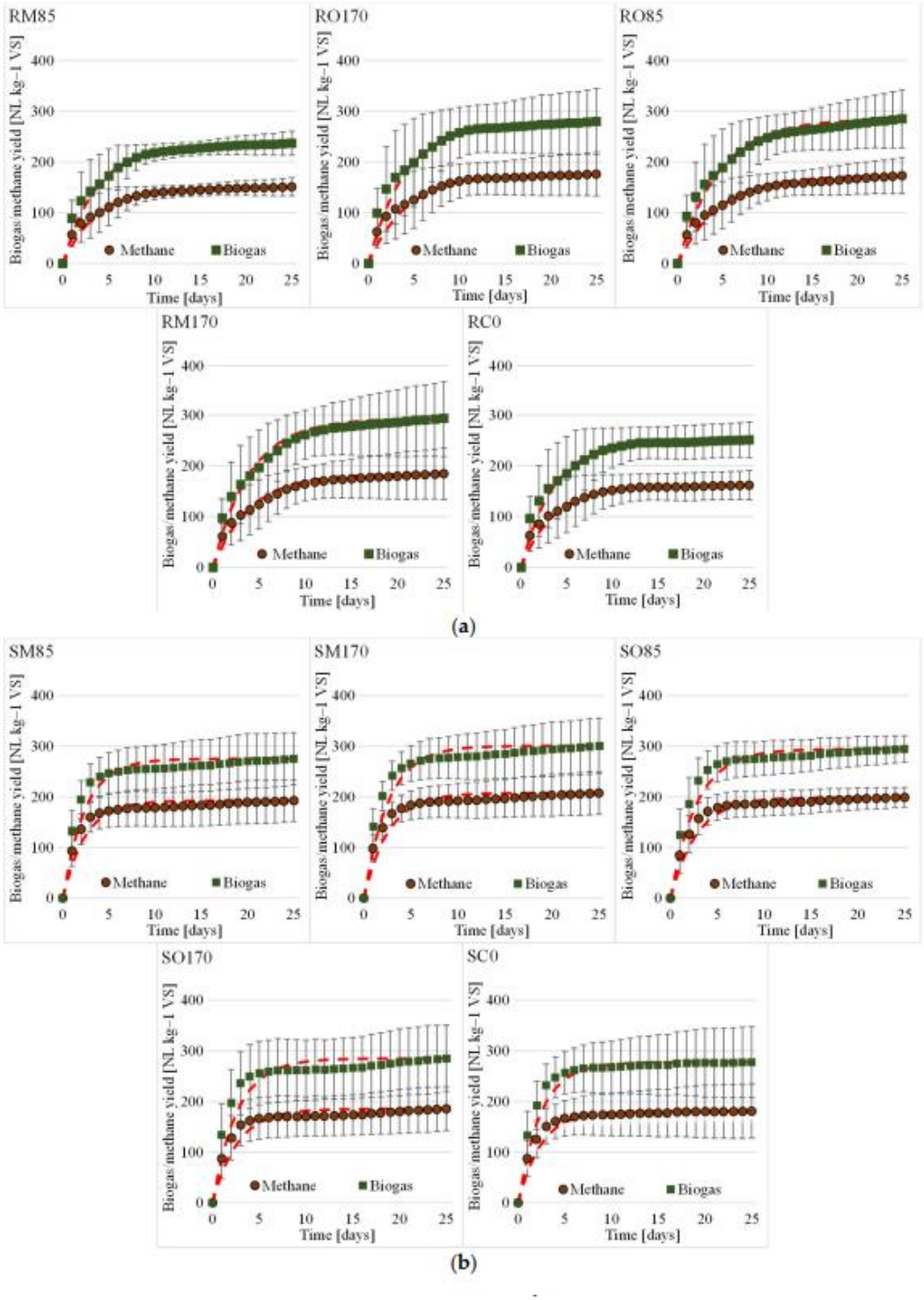


Figure 14. Cumulative biogas and methane yield (NL kg^{-1} VS) of *Helianthus salicifolius* as silage and raw biomass in the 25-day test, depending on the type of fertilization (kg N ha^{-1}): C0 – without fertilization, O85 – organic fertilization 85, M85 – mineral fertilization 85, M170 – mineral fertilization 170, O170 – organic fertilization 170. (a) *Helianthus salicifolius* as raw biomass (R); (b) *Helianthus salicifolius* as silage (S).

7.3. Biomass and silage of *Silphium perfoliatum* as a feedstock for biogas production

The *Silphium perfoliatum* biogas potential where were investigated different fertilization types and rates, which influences on the feedstock features and biomethane production. The biomethane measurements were provided on raw green biomass and silage. The feedstock and digestate characteristics were investigated as well. Thus, in the Table 1 is presented the anaerobic sludge characteristics used as the inoculum for the fermentation process and in the Table 2 is presented biomass characteristics of the *Silphium perfoliatum* used as the feedstock for experimental trials for biogas production.

Table 1. Characteristics of anaerobic sludge used as the inoculum for the fermentation process in bioreactors.

Item	Inoculum
DM	7.1 ± 0.3
ODM	70.6 ± 2.9
Ash	29.4 ± 2.9
Carbon	40.4 ± 1.3
Nitrogen	3.9 ± 0.1
C/N ratio	10.2 ± 0.1

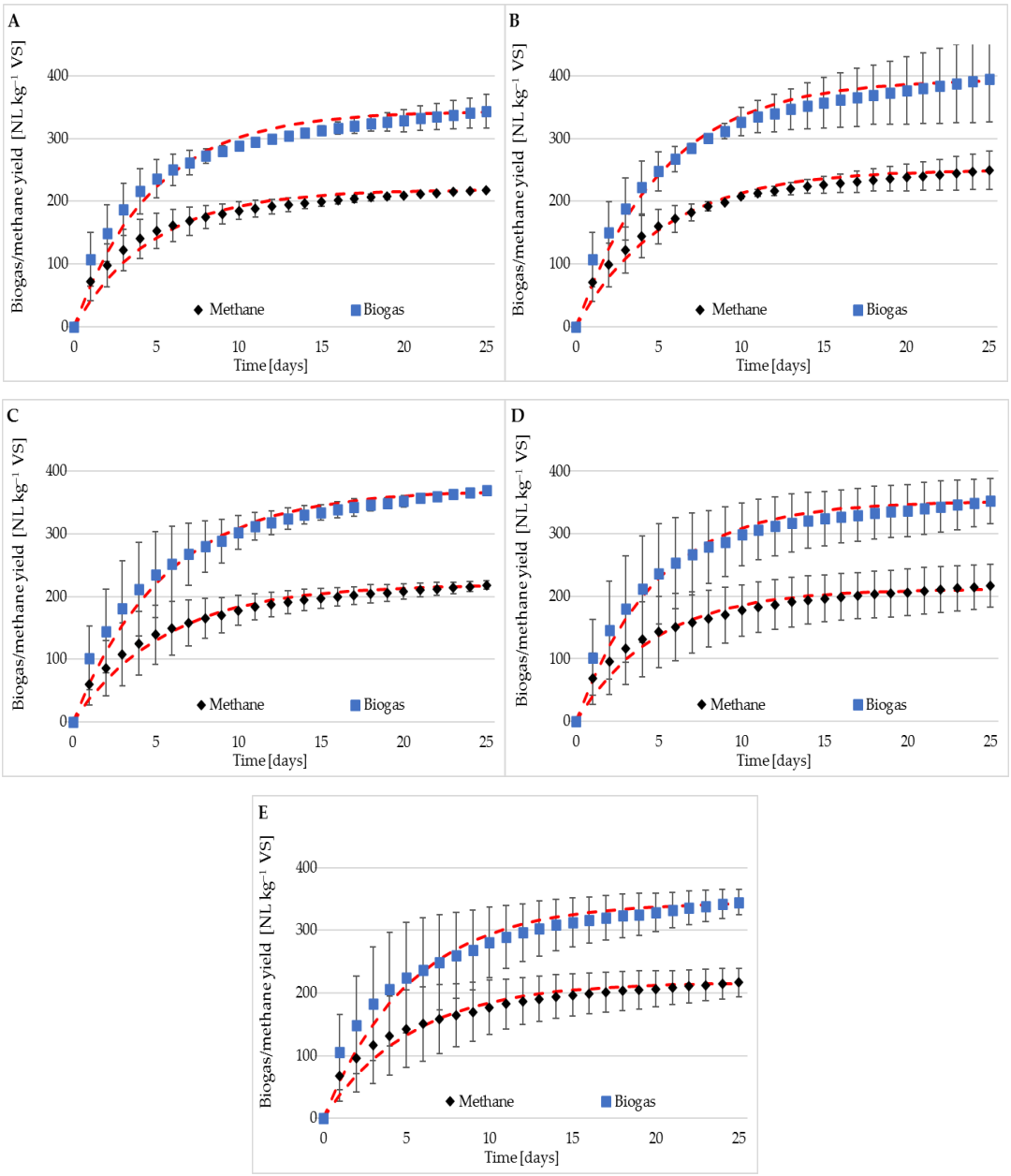
DM – dry mass (% d.m.); ODM –organic dry mass (% d.m.); Ash (% d.m.); Carbon (% d.m.); Nitrogen (% d.m.); C/N – carbon to nitrogen ratio.

Table 2. Characteristics of raw material and silage of *Silphium perfoliatum* used for the preparation of feedstock. (O85 – organic fertilization 85 kg ha^{-1} N; O170 – organic fertilization 170 kg ha^{-1} N; M85 – mineral fertilization 85 kg ha^{-1} N; M170 – mineral fertilization 170 kg ha^{-1} N; C – without fertilization).

Item	Substrate Type	O85	O170	M85	M170	C0
DM	Raw	22.9 ± 0.8	23.1 ± 0.7	25.3 ± 0.8	22.5 ± 0.6	22.9 ± 0.1
	Silage	21.4 ± 0.0	21.8 ± 1.1	21.1 ± 2.6	20.6 ± 1.9	20.6 ± 1.5
ODM	Raw	90.7 ± 0.2	90.3 ± 0.8	91.0 ± 1.5	92.0 ± 0.1	91.4 ± 0.8
	Silage	89.5 ± 0.1	89.7 ± 0.6	90.5 ± 1.1	91.9 ± 0.4	89.7 ± 0.1
Ash	Raw	9.3 ± 0.2	9.7 ± 0.8	9.0 ± 1.5	7.9 ± 0.1	8.6 ± 0.8
	Silage	10.5 ± 0.1	10.3 ± 0.6	9.5 ± 1.1	8.1 ± 0.4	10.3 ± 0.1
Carbon	Raw	43.7 ± 0.5	44.4 ± 1.1	43.6 ± 1.1	44.8 ± 1.0	43.7 ± 0.7
	Silage	45.1 ± 0.9	45.5 ± 0.0	44.9 ± 2.5	46.8 ± 1.1	45.4 ± 1.0
Nitrogen	Raw	0.8 ± 0.0	0.8 ± 0.0	0.9 ± 0.0	1.1 ± 0.3	0.7 ± 0.0
	Silage	0.9 ± 0.0	0.9 ± 0.0	1.0 ± 0.0	1.1 ± 0.1	0.8 ± 0.1
C/N ratio	Raw	62.3 ± 4.4	53.0 ± 1.2	47.6 ± 1.1	41.7 ± 10.6	61.4 ± 3.1
	Silage	53.3 ± 1.4	49.4 ± 0.4	46.4 ± 1.4	43.8 ± 3.9	54.5 ± 4.5

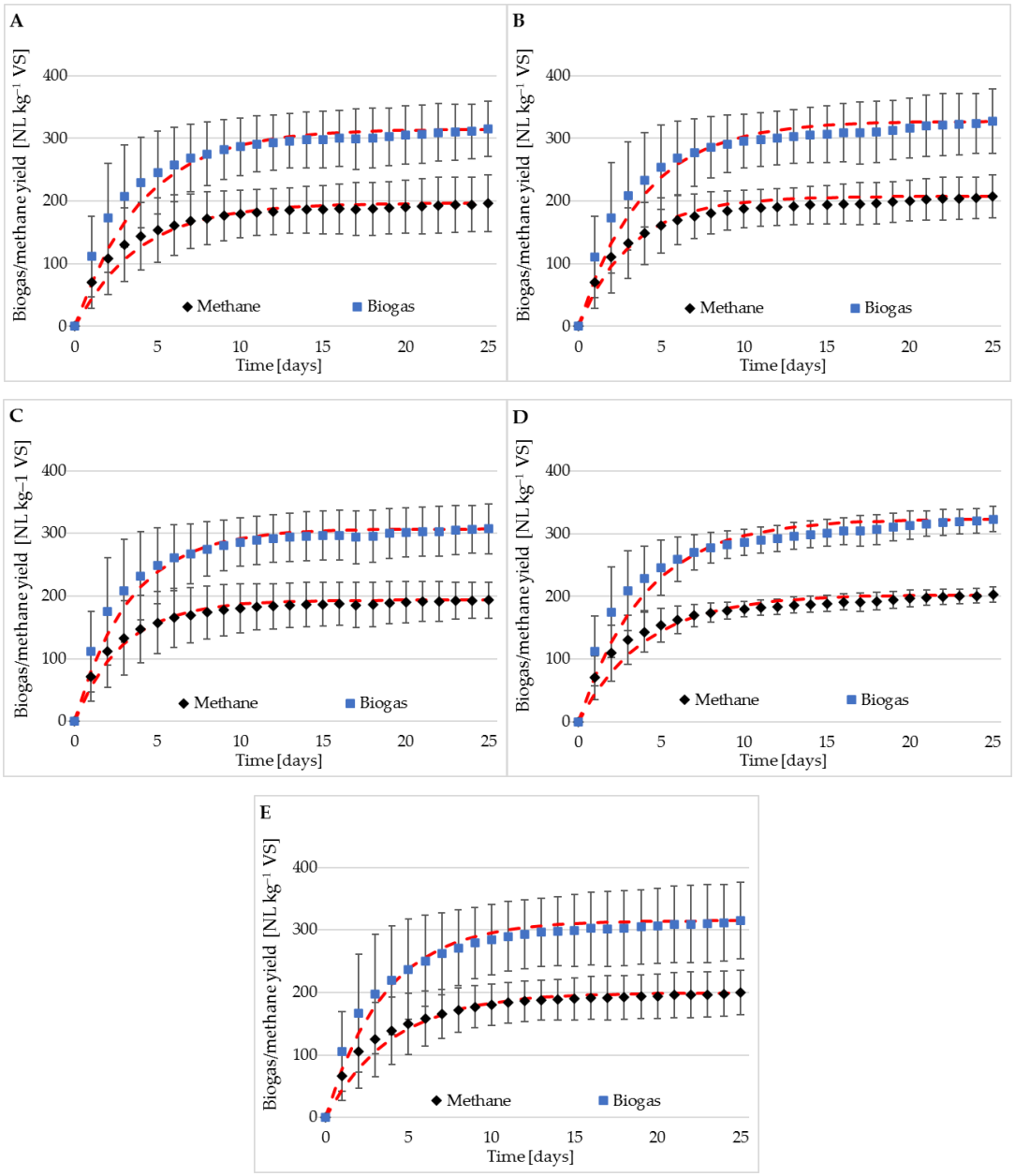
DM – dry mass (% d.m.); ODM –organic dry mass (% d.m.); Ash (% d.m.); Carbon (% d.m.); Nitrogen (% d.m.); C/N – carbon to nitrogen ratio.

The daily biogas and biomethane production outputs from raw substrates and silages of *Silphium perfoliatum* is presented in Figure 15a, b. The highest biogas and methane yield was achieved from raw material with the mineral fertilization dose of 170 kg ha^{-1} N (395.15 and 243.61 NL kg^{-1} VS, respectively), as well as 204.26 and 327.45 NL kg^{-1} VS, respectively from silage with the mineral fertilization dose 170 kg ha^{-1} N. Higher methane yields were obtained in Germany (on irrigated land) 310-321 NL kg^{-1} VS [22]. The methane and biogas production showed differences between substrate type, but there were not any significant statistical differences regarding biogas and methane production between fertilization type, and the N dose and between all interactions. In a similar study where different energy crops were investigated, it was found that the N dose significantly influenced the methane and biogas production (maize and sunflower), but was not a rule for all energy crops [23].



a) *Silphium perfoliatum* as raw biomass

Figure 15. *Cont*.



b) *Silphium perfoliatum* as silage

Figure 15. Cumulative methane and biogas yield (NL kg^{-1} VS) of *Silphium perfoliatum* as raw biomass and as silage in the 25 – day test, depending on the type of fertilization (kg ha^{-1} N): A) mineral fertilization 85, B) mineral fertilization 170, C) organic fertilization 85, D) organic fertilization 170, E) without fertilization.

7.4. The biomass yield, biogas and energy potential of *Silphium perfoliatum* and *Helianthus salicifolius*

Biomass yield, potential energy yield, the biogas and methane production efficiency of *Silphium perfoliatum* and *Helianthus salicifolius* biomass, are depending on different rates and type of fertilization. The study was conducted over three successive study years with the application of fertilizers at the beginning of the vegetation period and biomass harvesting in early September. It was founded that the application of fertilizers and a higher nitrogen level significantly contributed to the increasing of dry matter yield. However, only in first study year the dry matter yield of *Helianthus salicifolius* was 57% higher compared to the *Silphium perfoliatum.* However, the three-year mean dry matter yield of *Silphium perfoliatum* was significantly higher compared to the three-year mean yield of *Helianthus salicifolius*, being 8.0 and 6.7 Mg ha^{-1} y^{-1} DM, respectively. The highest biomass yield of *Silphium perfoliatum* (16.3 Mg ha^{-1} y^{-1} DM) was obtained in 2021 with mineral fertilization at 170 kg ha^{-1} N. Significantly higher yields in another study were in Lithuania (21.9 Mg ha^{-1} DM), Chile (22.3 Mg ha^{-1} DM), and in Poland (26.6 Mg ha^{-1} DM) [24-26].

The biogas yield and the methane percentage content were determined for the biomass obtained in 2019 and 2020. Mean values were calculated for each experimental plot for two years and were used for further calculations of biogas and methane production efficiency from 1 Mg DM for the three years of the experiment analyzed herein (2019-2021) (1):

B_{DM} or M_{DM} = B_{ODM} or M_{ODM} * (ODM / 100) (1)

where:

B_{DM} or M_{DM} - biogas or methane production efficiency from dry matter (m^3 Mg^{-1} DM),

B_{ODM} or M_{ODM} - biogas or methane production efficiency from dry organic matter (m^3 Mg^{-1} ODM),

ODM - organic dry matter content (% DM).

The efficiency of biogas and methane production from *Silphium perfoliatum* substrate was significantly higher compared to the substrate from *Helianthus salicifolius.* Meanwhile, the type or level fertilization did not have a significant impact on the methane or biogas efficiency. The potential biogas, methane and energy yield obtainable from 1 ha of *Silphium perfoliatum* or *Helianthus salicifolius* plantation (Table 3), was calculated in the next step. The dry matter yield and the biogas or methane production efficiency from dry biomass were used to calculate the potential biogas and methane yield from 1 ha (2):

BPY or MPY = DMY * B_{DM} or M_{DM} (2)

where:

BPY or MPY - biogas or methane potential yield (m^3 ha^{-1} y^{-1}),

DMY - dry matter yield (Mg ha^{-1} y^{-1} DM),

B_{DM} or M_{DM} - biogas or methane production efficiency from dry biomass (m^3 Mg^{-1} DM).

Table 3. Biogas potential yield (BPY) depending on the PHC species, type and level of fertilization and the harvest year (m^3 ha^{-1} y^{-1}); ± denotes standard deviation.

Item	Harvest year			Mean
	2019	2020	2021	
*S. perfoliatum*_organic_85 N	1872.7 ± 472.1	2689.7 ± 910.1	3335.6 ± 1158.1	2632.7 ± 1000.6
*S. perfoliatum*_organic_170 N	1868.6 ± 336.4	2524.4 ± 572.4	3609.7 ± 1505.9	2667.6 ± 1121.2
*S. perfoliatum*_mineral_85 N	1678.6 ± 416.5	3116.5 ± 368.3	3602.8 ± 539.2	2799.3 ± 949.1
*S. perfoliatum*_mineral_170 N	2055.4 ± 156.1	3429.5 ± 414.8	5988.5 ± 425.5	3824.5 ± 1755.7
*S. perfoliatum*_control_0 N	1199.3 ± 159.2	1556.2 ± 178.6	1775.4 ± 433.7	1510.3 ± 353.2
*H. salicifolius*_organic_85 N	1850.4 ± 221.6	1061.0 ± 161.0	804.6 ± 256.5	1238.7 ± 508.0
*H. salicifolius*_organic_170 N	2523.2 ± 622.7	1511.6 ± 654.9	1296.5 ± 607.3	1777.1 ± 786.2
*H. salicifolius*_mineral_85 N	2411.4 ± 92.1	1214.1 ± 395.3	1346.8 ± 319.9	1657.4 ± 624.4
*H. salicifolius*_mineral_170 N	3736.1 ± 244.9	2952.0 ± 469.5	2764.6 ± 773.5	3150.9 ± 647.2
*H. salicifolius*_control_0 N	1203.5 ± 209.9	739.7 ± 165.1	553.1 ± 99.7	832.1 ± 323.2
*S. perfoliatum*_mean	1734.9 ± 366.6	2663.3 ± 685.9	3662.4 ± 1210.8	2686.9 ± 1278
*H. salicifolius*_mean	2344.9 ± 348.9	1495.7 ± 390.5	1353.1 ± 1377	1731.2 ± 960.3
Organic_mean	2028.7 ± 479.1	1946.7 ± 894.4	2261.6 ± 1542.2	2079.0 ± 1043.7
Mineral_mean	2470.4 ± 839.2	2678.0 ± 967.4	3425.7 ± 1819.6	2858.0 ± 1315.0
Control_mean	1201.4 ± 158.8	1148.0 ± 450.9	1164.3 ± 692.4	1171.2 ± 472.3
85 N_mean	1953.3 ± 498.0	2020.3 ± 973.6	2272.5 ± 1303.5	2082.0 ± 967.8
170 N_mean	2545.8 ± 935.9	2604.4 ± 1026.3	3414.8 ± 1947.0	2855.0 ± 1380.2
Organic_85 N_mean	1861.6 ± 330.1	1875.4 ± 1066.5	2070.1 ± 1576.3	1935.7 ± 1052.1
Organic_170 N_mean	2195.9 ± 573.5	2018.0 ± 781.2	2453.1 ± 1630.9	2222.3 ± 1045.1
Mineral_85 N_mean	2045.0 ± 483.6	2165.3 ± 1096.6	2474.8 ± 1297.7	2228.4 ± 976.0
Mineral_170 N_mean	2895.8 ± 938.7	3190.8 ± 474.8	4376.6 ± 1852.0	3487.7 ± 1329.6
Year_mean	2039.9 ± 765.5	2079.5 ± 1005.5	2507.8 ± 1678.0	2209.1 ± 1214.3

The mean of potential energy yield from *Silphium perfoliatum* was significantly higher by 52.3% compared to the mean value of *Helianthus salicifolius* (Table 4). The highest potential energy yield in the whole experiment (33,859.9 kWh ha^{-1} y^{-1}) was obtained in 2021 from *Silphium perfoliatum* biomass with mineral fertilisation at 170 kg ha^{-1} N.

Subsequently, the potential energy yield from 1 ha was calculated (3):

PEY = MPY * 9.17 (3)

where:

PEY - potential energy yield (kWh ha^{-1} y^{-1}),

MPY - methane potential yield (m3 ha^{-1} y^{-1}),

9.17 - methane calorific value (kWh m^{-3}).

Table 4. The potential energy yield (PEY) depending on the PHC species, type and level of fertilisation and the harvest year (kWh ha^{-1} y^{-1}); ± denotes standard deviation.

Item	Harvest year			Mean
	2019	2020	2021	
*S. perfoliatum*_organic_85 N	10,492.9 ± 2839.5	15,082.8 ± 5320.1	18,657.0 ± 6566.8	14,744.2 ± 5695.1
*S. perfoliatum*_organic_170 N	10,640.3 ± 2135.0	14,349.2 ± 3348.3	20,607.1 ± 8820.6	15,198.9 ± 6513.4
*S. perfoliatum*_mineral_85 N	9494.6 ± 2579.4	17,590.8 ± 2465.3	20,346.7 ± 3510.7	15,810.7 ± 5488.9
*S. perfoliatum*_mineral_170 N	11,621.7 ± 883.7	19,391.8 ± 2385.7	33,859.9 ± 2481.6	21,624.5 ± 9934.2
*S. perfoliatum*_control_0 N	6866.8 ± 870.6	8922.4 ± 1109.1	10,166.5 ± 2464.3	8651.9 ± 2024.3
*H. salicifolius*_organic_85 N	10,299.8 ± 1231.5	5907.6 ± 897.7	4478.9 ± 1427.0	6895.4 ± 2826.9
*H. salicifolius*_organic_170 N	14,568.1 ± 3599.0	8704.5 ± 3692.7	7467.4 ± 3448.6	10246.7 ± 4518.0
*H. salicifolius*_mineral_85 N	14,097.7 ± 511.3	7094.5 ± 2297.0	7871.5 ± 1860.8	9687.9 ± 3647.1
*H. salicifolius*_mineral_170 N	21,566.9 ± 1448.5	17,027.5 ± 2561.2	15,940.2 ± 4347.0	18,178.2 ± 3683.7
*H. salicifolius*_control_0 N	7123.2 ± 1266.8	4379.6 ± 996.1	3272.4 ± 598.0	4925.1 ± 1920.0
*S. perfoliatum*_mean	9823.3 ± 2248.3	15,067.4 ± 3995.9	20,727.4 ± 7036.4	15,206.0 ± 7242.1
*H. salicifolius*_mean	13,531.1 ± 2081.1	8622.7 ± 2383.4	7806.1 ± 7885.1	9986.6 ± 5520.5
Organic_mean	11,500.3 ± 2892.0	11,011.0 ± 5091.7	12,802.6 ± 8782.8	11,771.3 ± 5967.2
Mineral_mean	14,195.2 ± 4943.3	15,276.2 ± 5428.2	19,504.6 ± 10,207.6	16,325.3 ± 7422.0
Control_mean	6995.0 ± 936.6	6651.0 ± 2537.0	6719.5 ± 3911.6	6788.5 ± 2670.2
85 N_mean	11,096.3 ± 2898.4	11,418.9 ± 5472.0	12,838.5 ± 7317.0	11,784.6 ± 5450.6
170 N_mean	14,599.3 ± 5402.4	14,868.3 ± 5789.7	19,468.7 ± 11003.9	16,312.1 ± 7820.5
Organic_85 N_mean	10,396.4 ± 1960.3	10,495.2 ± 6074.5	11,568.0 ± 8852.6	10,819.9 ± 5944.0
Organic_170 N_mean	12,604.2 ± 3410.7	11,526.9 ± 4415.6	14,037.3 ± 9363.4	12,722.8 ± 6005.2
Mineral_85 N_mean	11,796.2 ± 3020.3	12,342.7 ± 6131.3	14,109.1 ± 7280.4	12,749.3 ± 5510.1
Mineral_170 N_mean	16,594.3 ± 5551.9	18,209.7 ± 2564.7	24,900.1 ± 10,313.0	19,901.4 ± 7481.4
Year_mean	11,677.2 ± 4433.8	11,845.1 ± 5673.2	14,266.8 ± 9478.5	12,596.4 ± 6878.1

Silphium perfoliatum on economic analysis confirmed that is more prospective PHC species as a biomass source for biogas plants (Table 5). The economic analysis of PHC biomass use for electric energy generation was based on the price of 1 kWh of energy based on the reference price of electric energy from renewable energy sources, which amounted to 0.71 PLN kWh^{-1} in Poland (i.e. 0.1581 € kWh^{-1}) (for 2019,2020 and 2021). The electric energy generation efficiency in a biogas plant was 38%. The biomass production cost was then calculated (4):

$$PI = (PEY * 0{:}1581 * 0{:}38) - Cp \quad (4)$$

where:

PI - potential income (€ ha^{-1} y^{-1}),

PEY - potential energy yield (kWh ha^{-1} y^{-1}),

0.1581 - average electric energy sale price (€ kWh^{-1}),

0.38 - electric energy production efficiency index,

Cp - biomass production cost (€ ha^{-1} y^{-1}).

Table 5. Potential income from electric energy generation in a biogas plant depending on the PHC species, type and level of fertilisation and the harvest year (€ ha^{-1} y^{-1}).

Item	Harvest year			Mean
	2019	2020	2021	
*S. perfoliatum*_organic_85 N	48.1	188.4	370.2	202.2
*S. perfoliatum*_organic_170 N	-75.1	21.4	280.0	75.4
*S. perfoliatum*_mineral_85 N	3.0	297.0	442.4	247.5
*S. perfoliatum*_mineral_170 N	-33.5	270.3	958.2	398.3
*S. perfoliatum*_control_0 N	23.4	90.4	154.2	89.3
*H. salicifolius*_organic_85 N	89.8	-97.1	-153.7	-53.7
*H. salicifolius*_organic_170 N	138.9	-108.8	-154.0	-41.3
*H. salicifolius*_mineral_85 N	215.3	-88.1	-46.9	26.8
*H. salicifolius*_mineral_170 N	461.4	245.6	216.8	307.9
*H. salicifolius*_control_0 N	52.1	-48.8	-93.3	-30.0
*S. perfoliatum*_mean	-6.8	173.5	441.0	202.6
*H. salicifolius*_mean	191.5	-19.4	-46.2	42.0
Organic_mean	50.4	1.0	85.6	45.7
Mineral_mean	161.6	181.2	392.6	245.1
Control_mean	37.8	20.8	30.5	29.7
85 N_mean	89.1	75.1	153.0	105.7
170 N_mean	122.9	107.1	325.3	185.1
Organic_85 N_mean	69.0	45.7	108.3	74.3
Organic_170 N_mean	31.9	-43.7	63.0	17.1
Mineral_85 N_mean	109.2	104.5	197.8	137.2
Mineral_170 N_mean	214.0	258.0	587.5	353.2
Year_mean	92.3	77.0	197.4	122.2

8. Conclusions

Based on the results obtained in this study, plant development varied significantly depending on the species and the type of fertilization, depending on the harvest year varied the number of platns and their height. Moreover, the species, fertilization type and N fertilization level significantly influenced most of the thermophysical and chemical features of PHC green biomass. The *Silphium perfoliatum* biomass contained more moisture, ash, chlorine, cellulose and lignin, whereas the *Helianthus salicifolius* biomass was characterized by higher contents of higher heating value, fixed carbon, carbon, hydrogen, sulfur and hemicellulose.

The application of organic and mineral fertilization resulted in a decrease in moisture, ash and lignin contents. However, this treatment slightly increased the higher heating value and significantly increased the chlorine, hemicellulose and cellulose content.

Application of the nitrogen dose of 170 kg ha^{-1} slightly increased the moisture, higher heating value, volatile matter, carbon, hydrogen, sulphur, total nitrogen, chlorine, hemicellulose and cellulose contents. Therefore, the species, fertilization type and N fertilization level significantly influenced most of the thermophysical and chemical features of PHC green biomass.

Considerably more biogas and methane can be obtained from *Silphium perfoliatum* than *Helianthus salicifolius*. *Silphium perfoliatum* proved to be a more prospective PHC species as a biomass source for biogas plants. It was found that the fertilization type, and N doses have no significant influence on the biomethane and biogas production. The economic analysis also confirmed that *Silphium perfoliatum* was a more prospective species, as the potential income from electric energy generation from the species biomass in a biogas plant it was higher (482%) compared to the mean level for *Helianthus salicifolius*.

Results from the present thesis clearly shows that biogas, methane and energy potential yield of *Silphium perfoliatum* was over 50% higher compared to the values of *Helianthus salicifolius.* In other words, *Silphium perfoliatum* proved to be a more prospective PHC species as a biomass source for biogas plants.

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