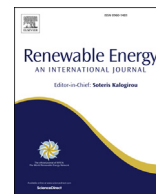




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## The quality and energy potential of introduced energy crops in northern part of temperate climate zone

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### ABSTRACT

Global climate change concomitant necessitates search for alternative and renewable energy generation systems as they reduce the greenhouse gas emissions. In warm climate, the productivity and the profitability of the perennial crops are high while in northern European countries the biomass DM yields are significantly lower. The aim of this study is to identify the potential crops from *Artemisia dubia*, *Miscanthus giganteus*, *Sida Hermaphrodita* for bioenergy, evaluate the biomass quality and energy potential in comparison with the traditional *Festuca arundinacea* grass, cultivated under the northern European-Lithuanian-weather conditions. Crops were grown with the applied 90 or 170 kg ha<sup>-1</sup> of mineral nitrogen fertilizer. The biomass quality varied significantly with the grass species and fertilization rate. The productivity of crops varied between the species and the highest of 21.54 t of DM ha<sup>-1</sup> was obtained from *Miscanthus giganteus* fertilized with 170 kg N ha<sup>-1</sup>. Most of the models available in the literature suggest that these crops are not economically feasible in Northern part of temperate climate zone due to the short vegetation season and very cold winters. However, the results obtained here suggest that under constantly changing climate conditions *Miscanthus giganteus*, may be promising feedstock for renewable energy.

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### 1. Introduction

An increased interest in climate change mitigation and renewable energy generation drives the search for biomass sources with improved DM yields. Cultivation of energy crops can optimize land management and may contribute to the reduction of global warming [1]. Van Dam et al. [2] indicated that most European countries have additional land available for cultivation of the energy crops. In most countries, the development of energy crops is focused on increasing the profitability during the growth, pre-treatment and energy production steps [3]. Typically, governmental policies, subsidies and regulations play a significant role in bioenergy development and the overall profitability of the bioenergy sector [3,4]. However, an adequate selection of the energy crops is the key profitability parameter that needs to be carefully assessed early in the planning process.

In northern European countries, annual crops have been preferred due to environmental and economic considerations. Their price is lower and farmers have more experience in growing them; hence, it is easier to incorporate these energy crops into rotation [5]. Nevertheless, in most northern European countries, perennial crops, especially non-food crops, play a key role in the bioenergy sector [6–10]. Perennials have more advantages compared to annuals as they may grow in one place for a few years without the need for re-cultivation; their root system is highly developed and strong making them more drought- and frost-resistant compared to annual crops [7]. Not only does the use of perennial herbaceous plants contribute to the growth of the bioeconomy sector but also it plays a significant role in preserving the biodiversity. The use of high-yielding agricultural crops is of particular interest in the global bioenergy sector [11–14]. In warm climate countries, the productivity of energy crops is significantly higher compared to that in northern countries [15,16], leading to better results towards bioenergy generation. Adapting high-yielding crops to different climate conditions hence is of high

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importance for bioenergy production in northern European countries.

While searching for potential energy crops, special attention is given to *Miscanthus giganteus* (*M. giganteus*), which is suitable for the production of heat, biogas, and bio-liquids [15–22]. The highest productivity of this crop is obtained in warm climate countries [14,23], where *M. giganteus* can be grown for more than 20 years in one place and biomass DM yields exceed those of most other crops. Hastings et al. [24], through modelling experiments identified that the most suitable area for growing *M. giganteus* is central Europe. Although *M. giganteus* can also be cultivated in northern European countries, there is a risk that it would not survive low winter temperatures. Research conducted in Denmark showed that the DM productivity of this crop in cool climate zones may reach up to 18 t ha<sup>-1</sup> [25]. Similar results were obtained in Poland, where *M. giganteus* was selected as a promising energy crop [3,11]. *M. giganteus* significantly improved soil properties and increased carbon sequestration [26]. However, studies on the cultivation of *M. giganteus* in temperate climate zones are scarce, especially on its bioenergy potential.

Another promising crop is *Artemisia dubia* (*A. dubia*). In southern countries, *A. dubia* has been used as raw material for the production of essential chemicals used in medicine [27–29]. The results of the initial experiments in Lithuania suggest that under optimal growing conditions, the biomass productivity may exceed 20 t ha<sup>-1</sup> of DM [30–32]. However, due to limited data availability, *A. dubia* has not yet been suggested as a potential bioenergy plant.

Finally, Kurutz et al., 2018 indicated that *Sida hermaphrodita* (*S. hermaphrodita*) may yield up to 10.2–11.9 t ha<sup>-1</sup> of DM under optimal growing conditions [33] and is suitable to obtain various bioproducts [33,34]. But most of the data were obtained for warm climate conditions; therefore more analysis is needed before the introduction to the Northern part of Europe.

Traditional perennial grasses may also be cultivated as potential energy crops. Studies suggest that local perennial grasses may be used for biogas production. In the Northern parts of the temperate climate region, one of the most productive grasses used for biogas production is tall fescue *Festuca arundinacea* (*F. arundinacea*) [10,35]. The crop has good overwintering abilities, productivity and biomass chemical composition suitable for biogas production. However, research on the influence of fertilization on *F. arundinacea* used for pelleting and burning is scarce and incomplete [36,37]. More in-depth studies are therefore necessary for the evaluation of traditional grasses as raw material for heat generation. Similarly, appropriate agricultural management may stimulate plant productivity and quality. Biomass productivity of most crops is increased by fertilization [8,10,35,36,38], although this is not the case for all energy crops [18]. There is no sufficient information about how fertilization influences the productivity of the non-traditional energy crops in northern climate conditions.

The aim of this study is to identify the potential crops for bio-energy, evaluate the biomass quality and energy potential of the introduced energy crops *A. dubia*, *M. giganteus*, *S. hermaphrodita* in comparison with the traditional grass *F. arundinacea*, as cultivated under Lithuanian climate.

## 2. Materials and methods

### 2.1. Field experiments

Field experiments were conducted at the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry (Central Lowland of Lithuania, 55°24' N, 23°52' E), in 2013 on an Endocalcari-Endohypogleyic Cambisol (CMg-n-w-can). The soil chemical characteristics of the 0–20 soil layer are presented in

Table 1.

The experiment was laid out in a randomized block design with a size of 21 m<sup>2</sup> (3 × 7 m). The two-way experiment involved three crops and two levels of mineral nitrogen fertilization (90 and 170 kg ha<sup>-1</sup>) and four replications. *A. dubia* was planted using plantlets at a density of two plants m<sup>-2</sup>. *M. giganteus* was planted at the same density using rhizomes at an inter-row spacing of 50 cm. Tall fescue cv. “Navas”, developed in Lithuania, was selected for the experiment as a traditional crop for the comparison. The seed rate of tall fescue was 18 kg ha<sup>-1</sup>. In the first year, no fertilizer was applied. In 2014 and 2015, the plots were fertilized with 90 and 170 kg ha<sup>-1</sup> of ammonium nitrate (N90 and N170, respectively). Fertilizer treated trials were compared to the control trials without fertilization.

*A. dubia* and *M. giganteus* were harvested in the winter when the crops were dry and had no green leaves. *A. dubia* was harvested at the beginning of December and *M. giganteus* - at the beginning of January. *F. arundinacea* was harvested twice a year. The first harvest was performed in July (after the flowering) and the second - at the beginning of October (at the end of the vegetation phase). Tall fescue swards were harvested using the harvester Hege 212 (Hege, Germany), while *M. giganteus* and *A. dubia* were harvested using a grass trimmer.

### 2.2. Weather conditions

The weather conditions varied during the experiment duration. In 2014, the rate of precipitation in Spring and Summer was close to the long-term average. Below normal precipitation rate was in 2015, except for September. The average monthly air temperature and the cumulative precipitation are shown in Fig. 1.

### 2.3. Chemical analysis

Chemical analysis was performed at the Chemical Research Laboratory of the Institute of Agriculture LAMMC, while the biomass energy potential was measured at Aleksandras Stulginskis University, Laboratory of Biomass Treatment, Logistics and Solid Fuel Processes. Fresh plant samples (above-ground biomass) were chopped into 3–5 cm particles and dried at 65 ± 5 °C. For chemical analysis, the samples were ground in a cyclonic mill and sieved via a 2-mm mesh size. All chemical analyses were in triplicate. The content of carbon (C), nitrogen (N) and sulfur (S) was determined using dry combustion in an oxygen atmosphere at 1,145 ± 5 °C according to the Dumas principle, using a fully automatic Vario EL III analyzer (Elementar, Germany). After wet digestion with sulphuric acid, the content of phosphorus (P) was determined spectrophotometrically at the wavelength of 430 nm while the content of potassium (K) was determined using atomic absorption. The content of neutral detergent fiber (NDF), acid detergent fiber (ADF) as well as acid detergent lignin (ADL) was determined using the cell wall detergent fractionation method according to Van Soest (Faithfull, 2002). The content of structural carbohydrates was calculated according to Hindrichsen, Kreuzer, Madsen, & Knudsen, 2006 -the content of cellulose:

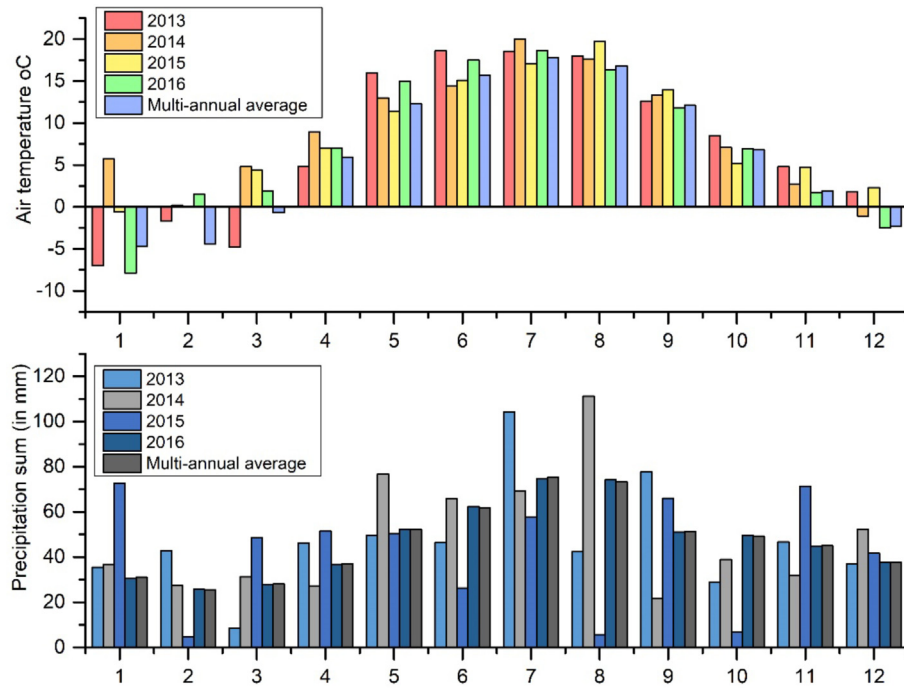
$$\text{Cell} = \text{ADF} - \text{ADL}, \quad (1)$$

the content of hemicellulose:

$$\text{HCell} = \text{NDF} - \text{ADF}. \quad (2)$$

**Table 1**  
Soil chemical composition.

Values %				
N <sub>sum</sub>	C <sub>org</sub>	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	pH
0.611	7.93	0.300	0.075	6.56



**Fig. 1.** Average monthly air temperature and cumulative precipitation in 2013–2016.

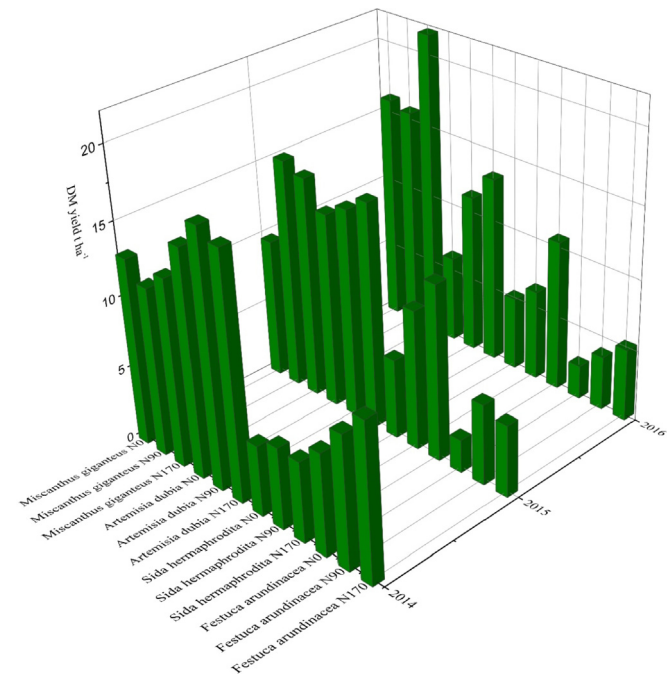
#### 2.4. Determination of energy potential

IKA C2000 calorimeter was used to measure the heating value at 25 °C using a dynamic calorific method. The pellets were formed from the ground biomass using a hand press and burned in the calorific bomb. Each treatment consisted of five replicates. The biomass energy potential was calculated according to the biomass DM yield per hectare and the biomass heating value.

Two-way analysis of variance was used for the statistical analysis of biomass productivity and biomass quality using SAS 9.4 software. The relationship between the biomass DM yield, energy potential, neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) content was evaluated using the correlation coefficient. Statistical inferences were made at the 0.05 significance level.

### 3. Results

Annual biomass productivity of *A. dubia*, *M. giganteus*, *S. hermaphrodita* and *F. arundinacea* are presented in Fig. 2. It can be seen that for the first two years of the experiment, *M. giganteus* and *A. dubia* were the most productive crops. The highest biomass DM yield of these crops was obtained in swards fertilized with either 90 or 170 kg N ha<sup>-1</sup>. The higher rate of nitrogen fertilization in 2014 and 2015, in general, resulted in higher DM yields, compared to non-fertilized plants. After the third year, the biomass DM yield from *A. dubia* decreased and *M. giganteus* resulted in the highest yield. The swards fertilized with 170 t N ha<sup>-1</sup> yielded 21.54 ± 0.37 t of DM per hectare.



**Fig. 2.** Biomass productivity at the harvest of *M. giganteus*, *A. dubia* and *F. arundinacea*.

The traditional grass *F. arundinacea*, as well as *S. hermaphrodita*,

had the lowest biomass DM yield. The annual DM yield of crops varied from 2.34 t ha<sup>-1</sup> to 10.99 t ha<sup>-1</sup> and from 4.96 ± 0.63 t ha<sup>-1</sup> to 12.3 ± 0.72 t ha<sup>-1</sup> of swards unfertilized and fertilized with 170 kg ha<sup>-1</sup>, respectively. The results of the three-year harvest of herbaceous energy crops suggest that the highest productivity was achieved for *M. giganteus* and *A. dubia* swards, while the traditional *F. arundinacea* grass produced the lowest biomass DM yield.

There were no significant differences in selected biomass chemical composition between the years; therefore, the average data are presented. However, the data for the biomass chemical composition presented in Fig. 3 show significant differences between the three evaluated energy crop species (Table 2).

In particular, fertilization significantly influenced C and N accumulation in the biomass. C concentration in above-ground biomass varied between 45 and 49% and decreased in the order:

*A. dubia* > *M. giganteus* > *S. hermaphrodita* > *F. arundinacea*

N and S concentrations in the above-ground biomass varied

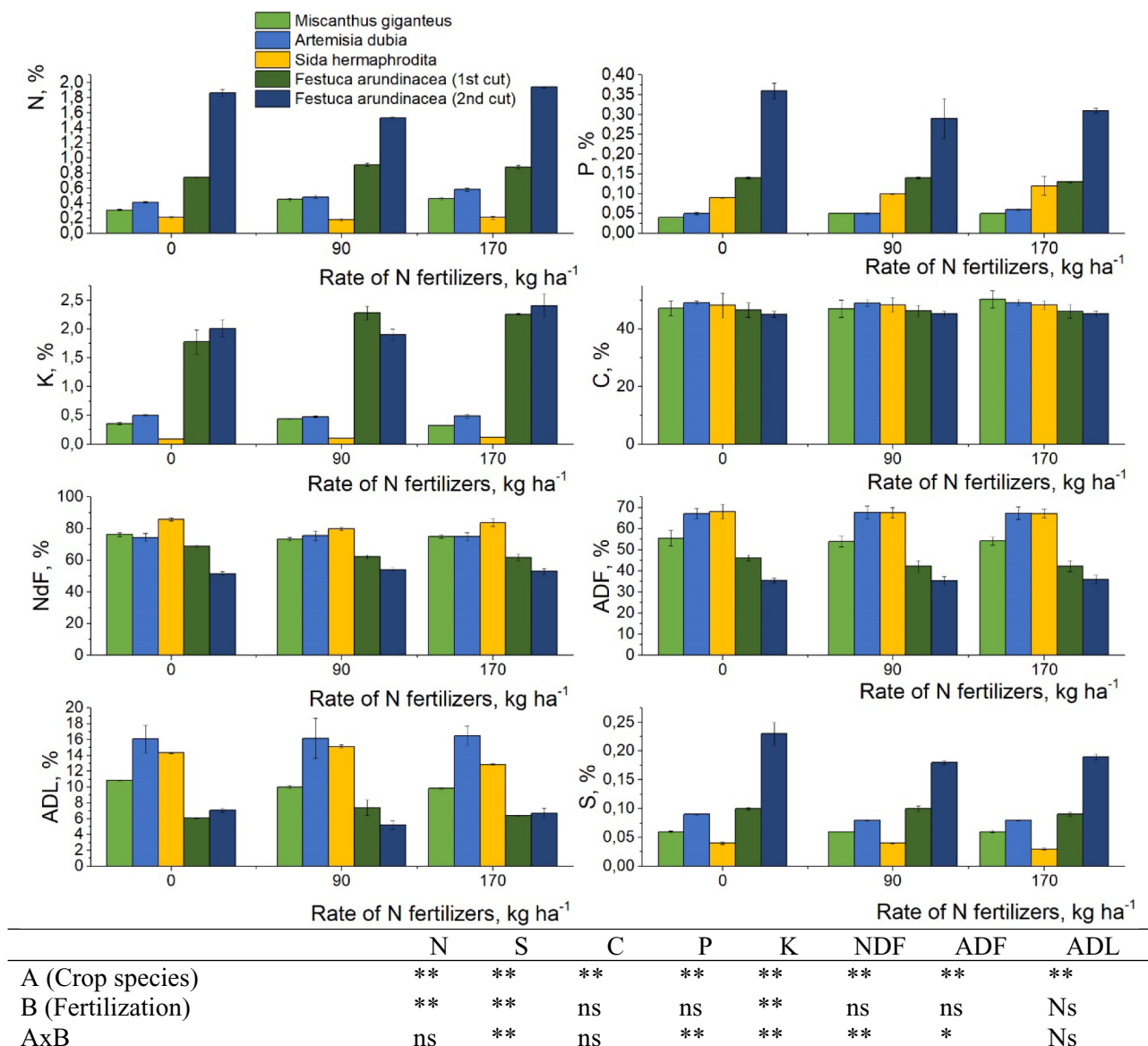
**Table 2**

The significance of DM biomass yield.

	2014	2015	2016
A (Crop species)	**	**	**
B (Fertilization)	ns	*	*
AxB	ns	ns	ns

greatly from 0.3 to 2.3% and 0.06–0.18%, respectively. Interestingly, N and S concentrations in the above-ground biomass decreased with increasing C content. The concentration of K and P in *M. giganteus* and *A. dubia* varied between 0.21–0.59% and 0.03–0.07%, respectively, while the concentration of these elements in *F. arundinacea* biomass varied between 2.15 to 2.76% and 0.14–0.31%, respectively. The interaction of crop species and fertilization affected the N and K concentrations.

The highest concentration of N, S, P and K was obtained in *F. arundinacea* biomass, while *A. dubia* presented the highest content of C and lignin. Both *M. giganteus* and *A. dubia* had significantly



**Fig. 3.** Chemical composition of aboveground biomass of *A. dubia*, *M. giganteus* and *F. arundinacea* in 2014–2016.



lower P and K concentrations compared to *F. arundinacea*. Nitrogen fertilization significantly increased the concentrations of N and decreased S content in plant biomass. Cellulose is the major polysaccharide of plant cell walls. In our experiments its concentration varied, according to the plant species, between 31.5 and 53.8% in DM and decreased in the order:

*A. dubia* > *M. giganteus* > *F. arundinacea* > *S. hermaphrodita*

The concentration of hemicellulose also varied according to the plant species between 6.4 and 21.8% in DM and decreased in the order:

*M. giganteus* > *S. hermaphrodita* > *F. arundinacea* > *A. dubia*

There was no clear relationship between the contents of cellulose and hemicellulose and fertilization levels, rather a noticeable decrease in cellulose and hemicellulose content with increasing N fertilization. The concentration of lignin varied according to the plant species between 5.4 and 17% in DM and decreased in the order:

*A. dubia* > *S. hermaphrodita* > *M. giganteus* > *F. arundinacea*

The chemical composition of introduced energy crops was more suitable for the biomass burning process compared to traditional *F. arundinacea*.

The key parameter of the energy crops, their energy effectiveness, is described by their heating value. No significant differences were observed between the plants. The highest heating value was obtained of *A. dubia* and *F. arundinacea* biomass harvested at the end of the growth phase while *M. giganteus* and *S. hermaphrodita* yielded lower heating values. Nitrogen fertilization negatively affected the heating value of *F. arundinacea* harvested in mid-summer at the end of the flowering phase. It decreased from  $18.684 \pm 0.118 \text{ MJ kg}^{-1}$  in non-fertilized swards to  $18.417 \pm 0.193 \text{ MJ kg}^{-1}$  in swards fertilized with  $\text{N}_{90}$  and to  $18.590 \pm 0.140 \text{ MJ kg}^{-1}$  in swards fertilized with  $\text{N}_{170}$ . The opposite tendency was observed for the swards harvested at the end of the vegetation season. The heating value of this crop in non-fertilized swards was  $18.523 \pm 0.150 \text{ MJ kg}^{-1}$  and increased up to  $18.599 \pm 0.267 \text{ MJ kg}^{-1}$  and  $18.781 \pm 0.084 \text{ MJ kg}^{-1}$  in swards fertilized with  $\text{N}_{90}$  and  $\text{N}_{170}$ , respectively. Nitrogen fertilization positively affected the heating value of *A. dubia*. Increased nitrogen fertilization from 0 to 90 and 170  $\text{kg ha}^{-1}$  increased the heating value from  $18.500 \pm 0.662 \text{ MJ kg}^{-1}$  ( $\text{N}_0$ ) to  $18.534 \pm 0.116 \text{ MJ kg}^{-1}$  ( $\text{N}_{90}$ ) and  $18.782 \pm 0.185 \text{ MJ kg}^{-1}$  ( $\text{N}_{170}$ ).

Biomass quality as energy potential per hectare was also evaluated. The unfavorable weather conditions in 2015 reduced the biomass DM yield of the energy crops (except *M. giganteus* fertilized with mineral nitrogen); therefore, the bioenergy potential in this year was lower compared to that of 2014 as shown in Fig. 4. In 2015, the energy potential of *A. dubia* was 1.09–1.22 times lower compared to the previous year. The biggest reduction was observed for the energy potential of *F. arundinacea*, which in non-fertilized swards and swards fertilized with  $\text{N}_{90}$  and  $\text{N}_{170}$ , was 3.04, 1.63 and 2.17 times lower, when compared to that of the plants harvested in 2014. Nevertheless, the *M. giganteus* showed increasing energy potential, especially in the swards fertilized with  $\text{N}_{170}$  while the energy potential of other crops was variable or even decreased from year to year. The effect of nitrogen fertilization on the bioenergy potential correlated with the results obtained in the biomass productivity analysis. The three-year results suggested that under different fertilization schemes, the energy potential increased with the increase in fertilizer rate. Generally, *M. giganteus*

and *A. dubia* swards accumulated the highest energy potential while the traditional *F. arundinacea* DM yielded the lowest bioenergy potential.

The energy potential of all evaluated grasses was strongly correlated with the biomass DM yield as shown in Table 3 with the correlation coefficient of 0.998–0.999. The ADF concentration was correlated with the biomass DM yield, energy potential and NDF in biomass of *A. dubia* and *F. arundinacea*. Compared to this, in the biomass of *M. giganteus*, there was only a positive correlation between ADF and NDF.

## 4. Discussion

### 4.1. Biomass productivity

For all energy crops considered, the biomass productivity plays a significant role in the bioenergy generation system. Higher biomass DM yield increases bioenergetical potential per unit surface area and positively affects the economic viability of the system [3,5,11,16,35,38]. In northern countries, the biomass productivity of traditional grasses, which may be also used for bioenergy, is not very high [39,40], which explains the need for alternatives. *Miscanthus giganteus* is one such crop that could be alternatively used for the production of cellulosic compounds, biochemical substances and bioenergy. The productivity of this crop may be influenced by the growing region, genotype and agricultural management [41]. Its biomass DM yield significantly differs between the regions. Long-term experiments of growing *M. giganteus* in different parts of the world characterize it as a high-yielding energy crop. For example, the average productivity of *M. giganteus* in Central Italy was about  $28 \text{ t ha}^{-1}$  but can reach up to  $48 \text{ t ha}^{-1}$  [42]. In Northern America, the average biomass productivity of *M. giganteus* is  $22.4 \text{ t ha}^{-1}$  [43],  $22\text{--}29 \text{ t ha}^{-1}$  in Denmark [44],  $17\text{--}25 \text{ t ha}^{-1}$  in Germany [45,46] and  $13.7 \text{ t ha}^{-1}$  in Poland [47]. In this work, *M. giganteus* productivity varied from  $9.70$  to  $21.54 \text{ t ha}^{-1}$ . As the biomass DM yield was not dramatically lower compared to the countries where *M. giganteus* is widely used, it can be assumed a promising crop not only for warm climate regions, but also for temperate areas.

Most of the studies indicate that the biomass DM yield of *M. giganteus* is significantly influenced by the year of the sward growth. In the first growth year, the productivity of this crop is several-fold lower compared to that of the subsequent years [42,44–47]. Usually, the highest biomass DM yield is reached after the three years of plant growth [45,47]. In most of the traditional perennial grasses, biomass DM yield decreases continuously while the productivity of *M. giganteus* remains more or less stable [45]. Our results indicate that there was a slight decrease in the biomass DM yield in non-fertilized swards in 2015 compared to 2014 but this decrease was insignificant and can be a result of varying weather conditions rather than a trait of the genetic crop features. Nevertheless, in 2015 the swards fertilized with mineral fertilizer produced higher biomass DM yields compared to those harvested in 2014 and the tendency remained in 2016.

One of the main factors for optimal crop cultivation is soil nutrition and an appropriate use of fertilizers. Usually, mineral and organic fertilizers are used to improve overall productivity [25,38,45,47]. In some studies, even low rates of nitrogen fertilization ( $\text{N}_{80}$ ) increased biomass DM yield by  $5 \text{ t ha}^{-1}$  compared to non-fertilized swards [45]. In our work, nitrogen fertilization had no significant effect on *M. giganteus* biomass accumulation and in 2014 non-fertilized swards produced even higher biomass DM yields compared to swards fertilized with  $\text{N}_{90}$  and  $\text{N}_{170}$ . These results are in line with those obtained by Kołodziej et al. [47] who proved that fertilization does not always have a positive effect on

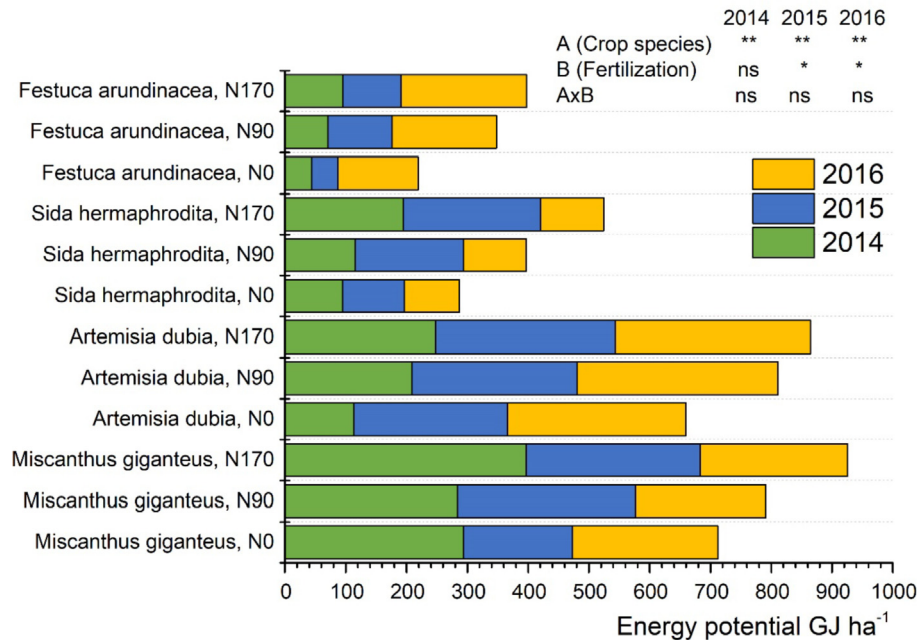


Fig. 4. The energy potential of *Artemisia dubia*, *Miscanthus giganteus*, *Sida hermaphrodita* and *Festuca arundinacea*.

Table 3

The correlation between the biomass energy potential, productivity, NDF, ADF and ADL.

	Biom.	Energy potential	NDF	ADF	ADL
<i>Artemisia dubia</i>					
Biom.	—				
En. pot	0.998*	—			
NDF	0.402	0.427	—		
ADF	0.547*	0.569*	0.926*	—	
ADL	0.631*	0.633*	0.306	0.468*	—
<i>Miscanthus giganteus</i>					
Biom.	—				
En. pot	0.999*	—			
NDF	0.090	0.093	—		
ADF	0.170	0.169	0.889*	—	
ADL	0.025	0.022	0.315	0.516*	—
<i>Festuca arundinacea</i>					
Biom.	—				
En. pot	0.999*	—			
NDF	0.588*	0.588*	—		
ADF	0.646*	0.645*	0.965*	—	
ADL	0.139	0.138	-0.027	0.081	—

Biom. — biomass DM yield, En. pot — energy potential, NDF — neutral detergent fibre, ADF — acid detergent fibre and ADL — acid detergent lignin.

biomass formation and productivity. In previous research, fertilization with sewage sludge negatively affected biomass accumulation; however, potential hazardous elements in the sludge may impede plant growth [47]. For the subsequent growth years, the growing intensity correlated to the nitrogen application and the higher rate of mineral nitrogen fertilization affected to higher DM yield of the crop.

In terms of biomass productivity for *A. dubia*, it is difficult to compare our results to the literature findings, as there is virtually no information about biomass accumulation for this species. *Artemisia dubia* is widely described as a potential raw material for medicine [29,48–50] due to its antimicrobial and antioxidant activities [51,52] and may be grown as an allelopathic crop [27]. However, the biomass productivity for this species is described in previous research conducted in different parts of Lithuania. The

biomass DM yield of this crop may vary from 3 t ha<sup>-1</sup> (in the first growing year) up to 35 t ha<sup>-1</sup> (in the third year) [30–32,53,54]. In present work, the highest biomass DM yield of 17.86 ± 1.198 t ha<sup>-1</sup> DM of *A. dubia* was obtained in the second growing year of 2014. Nevertheless, the decrease in biomass DM yield was found in 2016. It can be suggested that this crop needs more precise cultivation technology or optimization of plant density.

For warmer climate countries, *S. hermaphrodita* is a promising crop with high DM yields and has been described as a source of biomass appropriate for bioenergy generation [55–57]. In our experiments, this crop did not exhibit good biomass productivity and energy potential results. The biomass DM yield was in line with that of the traditional crops and about twice as low when compared to the *M. giganteus*.

For the comparison of the non-traditional energy crops with *M. giganteus*, *A. dubia* and *S. Hermaphrodita*, the native species *F. arundinacea* was selected. In Lithuania, the productivity of this crop grown under *Endocalcar-Endohypogleyic Cambisol* (CMg-n-w-can), fertilized with N<sub>180</sub> and harvested twice a year was 13.4 t ha<sup>-1</sup> [10,35]. In a previous study, *F. arundinacea* grown under irrigation DM yielded up to 12.5 t ha<sup>-1</sup> [58]. However, in the present study, the biomass DM yield of *F. arundinacea* was lower. The decrease in biomass productivity may be influenced by the growing conditions during the vegetation season.

In the present work, it was hypothesized that non-traditional introduced crops present higher productivity compared to traditional grasses. This hypothesis could be confirmed because the analysis of the variation of biomass DM yield within the different crops and levels of mineral nitrogen fertilizers suggested that the highest productivity of evaluated energy crops was achieved in *M. giganteus* (21.54 t ha<sup>-1</sup>) and *A. dubia* (17.86 t ha<sup>-1</sup>) swards. *S. hermaphrodita* (12.30 t ha<sup>-1</sup>) while the traditional crop *F. arundinacea* (10.99 t ha<sup>-1</sup>) produced the lowest biomass DM yield. This implies that if the biomass quality were appropriate for bioenergy production, *M. giganteus*, as well as *A. dubia* could be one of the most promising energy crops in northern climate zones. The findings of *M. giganteus* confirms the previous results of research conducted in Denmark and other Northern countries, but for

*A. dubia* that was the first time when this crop was grown in such climate conditions.

#### 4.2. Variation of the biomass chemical composition

Biomass is a complex heterogeneous mixture of organic matter and, to a lesser extent, inorganic matter. The chemical composition of raw material used for bioenergy production plays a significant role in the energy generation process. The chemical composition and the bioenergy potential of the biomass depend on the various factors, including plant species, growing conditions, age of plants, fertilizer doses and harvesting time [40,59]. In this study, the biomass of energy crops was analyzed as potential source for pelleting and combustion. The highest attention was paid to elements stimulating or inhibiting the heat production process.

The concentrations of N, S, P and K in the biomass play an important role in biomass combustion quality [60]. High concentration of N and S can result in increased emissions of NO<sub>x</sub> and SO<sub>2</sub> while high levels of K and P in the biomass are undesirable and can reduce the ash melting point and lead to corrosion [60,61]. The N and S concentrations in above-ground biomass decrease with the increase in C content which agrees with the results obtained in other experiments [59,62]. The highest carbon content was found for the biomass of *M. giganteus* and *A. dubia* and ranged from 48.50 to 52.7% in DM. It should be noted that most herbaceous plants are not suitable for thermal conversion due to their low-quality biomass, but in our research, the N and C content of evaluated introduced crops was similar to those of the woody plants, such as poplar [63,64]. The content of S in the biomass of non-traditional crops was in line with the results of corn residues [65] and more than 10 times lower compared to traditional grasses.

For energy generation purposes, one of the most important biomass parameters is the concentration of structural biopolymers. In particular, the stored chemical energy in plants is contained in the cellulose, hemicellulose and lignin components [66]. The higher concentrations of cellulose and lignin are desirable to use the biomass as a solid biofuel. The fiber fraction of the above-ground biomass influences biomass pelleting and burning processes. The highest contents of NDF and ADF were obtained for the biomass of *M. giganteus* and *A. dubia*. Those crops also produced the highest content of cellulose, while *A. dubia* yielded the lowest hemicellulose content. Lignin is the most valuable substance in the plant biomass when used as solid fuel because it is less oxidized than the structural polysaccharides and therefore has a higher energy content than cellulose and hemicellulose [67]. Lignin has a higher heating value compared to cellulose [63]. The introduced crop *A. dubia* had lignin and cellulose contents in the upper range (from 16.07 to 16.49%), while the lowest lignin concentration was determined for *F. arundinacea* at the first harvest (from 6.06 to 6.42%).

#### 4.3. Biomass heating value and energy potential

The profitability of thermal conversion process is mostly determined by the energy value of the raw material and its bioenergy potential as well as the energy input for crop management, harvesting and biofuel preparation. The energy input for all technological processes of using *A. dubia* for bioenergy was presented in previous research [68] and is similar for all crops grown in this experiment as the same technology was applied. It was indicated that the energy input varies from 8 to 12% of the total energy potential and there are no significant differences between the same fertilization treatments of different crops, the data was not detailed in this paper.

The calorific value of the biomass used as fuel depends on the C content because the major organic-forming element C is oxidized

during the exothermic reaction. In this work, the highest heating value was obtained for the biomass of *A. dubia* and *F. arundinacea* (harvested at the end of the vegetation phase). Depending on the nitrogen fertilization, the heating value of *A. dubia* varied from 18.5 to 18.8 MJ kg<sup>-1</sup> and that of *F. arundinacea* (second harvest) from 18.5 to 18.9 MJ kg<sup>-1</sup>. It is difficult to compare the results obtained for *A. dubia* with the findings of other studies as this species is mainly described as a source of essential oils or other components but not as a bioenergy crop. However, our results are in line with those achieved by the thermochemical conversion of willow [64] and therefore could be evaluated as a potential energy crop. Despite the fact that the heating value of *F. arundinacea* was similar to that found for *A. dubia*, the energy yield per unit of the cultivated surface was significantly higher for *A. dubia*. In this study, *F. arundinacea* produced a similar energy amount per hectare compared to the findings presented by Pocienė and Kadžiulienė (2016). There was a strong correlation between biomass DM yield and energy potential; similar results were found for other herbaceous crops [69].

In the present study, *M. giganteus* generated 179–397 GJ ha<sup>-1</sup> of thermal energy. Unfortunately, these results were almost twice as low compared to *M. giganteus* grown in warmer climate [42,70]. Nevertheless, it seems to be a promising crop for bioenergy production as its energy potential is higher than that of traditional grasses. It also should be noted that modelling results indicate that *M. giganteus* may become much more promising and cold-tolerant in the context of a changing climate [71].

## 5. Conclusions

The crops *M. giganteus* and *A. dubia* are potential energy crops in northern part of temperate climate zone. The highest productivity of evaluated energy crops was achieved in *M. giganteus* (21.54 t ha<sup>-1</sup>) and *A. dubia* (17.86 t ha<sup>-1</sup>) swards. *S. hermaphrodita* (12.30 t ha<sup>-1</sup>) and the traditional crop *F. arundinacea* (10.99 t ha<sup>-1</sup>) produced the lowest biomass DM yield.

Biomass quality varies between the crop species of crops. Non-traditional energy crops *Miscanthus giganteus* and *Artemisia dubia* presented a high concentration of carbon, cellulose and lignin and a lower concentration of inhibiting elements potassium and phosphorus compared to other evaluated crops. The biomass quality of those crops was in line with the results obtained by other researchers and may be compared to woody short-rotation forests. The higher energy value was determined for *A. dubia* and *M. giganteus*. The assessment of energy potential and energy efficiency showed differences in crops and was effectively proportional to the biomass DM yields but not to their energetic value.

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