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Perennial herbaceous crops as a feedstock for energy and industrial purposes: Organic and mineral fertilizers versus biomass yield and efficient nitrogen utilization

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ABSTRACT

Perennial herbaceous crops (PHC) could be a feedstock for energy and industrial purposes. Not much is known on the effect of fertilization of PHC with biogas plant digestate. The study analysed three forms of biogas plant digestate and mineral fertilizers on the yield PHC and nitrogen (N)-use efficiency in three consecutive harvest cycles. The PHC were: *Helianthus tuberosus*, *Sida hermaphrodita*, *Helianthus salicifolius*, and *Miscanthus* × *giganteus*. The forms of fertilization were: wet digestate, dry digestate, torrefied digestate, mineral fertilization and control (no fertilization). The level of N fertilization were: N 85 and 170 kg ha^{-1}.

Fertilization of PHC, except *Miscanthus* × *giganteus*, and an increase in the nitrogen rate generally increased the yield compared with the control plots. The highest yield of 15 Mg ha^{-1} DM was achieved for *Helianthus salicifolius* in the third year where mineral fertilization, dry digestate was applied and on the control plot. The yield of *Miscanthus* × *giganteus* and *Sida hermaphrodita* also increased in consecutive years, but it was much lower than *Helianthus salicifolius*. *Helianthus tuberosus* had an opposite yield relationship and gave the highest yield in the first year. The agronomic efficiency and recovery efficiency of applied N indices were the highest for HT and the lowest for MG. It could be stated that in the initial years of cultivation, from the perspective of yielding and nitrogen use efficiency, the fertilisation of PHC was partially justified, while it was not justified in *Miscanthus* × *giganteus*.

1. Introduction

Biomass has become the main renewable energy source (RES) in Poland and it accounted for 76% of all RES in 2015. Moreover, biomass is a raw material for the production of biogas and transport biofuels, which accounted for 5.5% and 6.7% of RES, respectively (CSO, 2016). The majority of biomass as energy and industrial feedstock is derived from forests. However, domestic policy has indicated an increased importance of agricultural biomass, including short rotation coppices (Krzyżaniak et al., 2015; Stolarski et al., 2015a) and perennial herbaceous crops (PHC) (Pudełko et al., 2012; Stolarski et al., 2014). These plants could be grown on soils of poorer quality, unusable for growing crops for food or fodder. The area of land in Poland which meets the usability criteria for perennial energy and industrial crops, is estimated to be 1.6 million ha (Pudełko et al., 2012). In consequence, there are a number of opportunities in Poland for production of biomass as energy feedstock and for industry. Depending on the species and the harvest date, biomass of perennial plants can be used directly as a solid fuel. It can also be used in biorefineries as feedstock for various bioproducts as well as liquid and gaseous biofuels (García et al., 2014; Godin et al., 2013; Kim and Kim, 2014; Klímek et al., 2016; Krzyżaniak et al., 2014; Scordia et al., 2016; Stolarski et al., 2013, 2015b,c).

Currently, maize is the most frequently used substrate for the production of biogas in Poland, Germany and other EU countries (Jankowski et al., 2016). Therefore, although the development of biogas plants boosts RES production growth, it also stimulates the competition for maize as feedstock for fodder and food production. Moreover, biogas plants co-produce digestate whose utilization as fertilizer is sometimes problematic due to its excessive amounts, varying crop sequence as well as time and quantity of nitrogen introduced to the soil with it. Therefore, cultivation of PHC creates opportunities: (i) to use soils of poor quality, (ii) to use biogas plant digestate as fertilizer,

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(iii) it can be a source of biomass as a substrate or co-substrate for a biogas plant, i.e. it is a potential supplement and replacement for maize and (iv) it can also be a feedstock for other industrial purposes.

However, in order to guarantee a stable supply of PHC biomass, new sustainable technologies of plant growing should be sought. The rate of nitrogen fertilization is one of the major factors which determine the plant yield. On the other hand, there is nitrogen use efficiency (NUE) in different plant species in the context of nitrogen loss and consequent negative environmental impact. NUE is an efficiency indicator that considers soil N supply, the fraction of N applied and taken up by the plant, and the efficiency indicator with which N uptake is converted into crop dry matter (Cassman et al., 2003; Ceotto et al., 2016). Not much is known on the effect of fertilization of PHC with biogas plant digestate. Therefore, the aim of the study was to determine: (i) the effect of three forms of biogas plant digestate and mineral fertilizers on the yield of four species of PHC; (ii) N-use efficiency for three forms of biogas plant digestate and mineral fertilizers applied to PHC, in three consecutive harvest cycles.

2. Materials and methods

2.1. Location and factors of the field experiment

A field experiment was set up in early May 2013 in north-eastern Poland (53°59′ N, 21°09′ E) at the Didactic and Research Station in Łężany owned by the University of Warmia and Mazury in Olsztyn. The four species of PHC: (i) Jerusalem artichoke (*Helianthus tuberosus* L.) (HT); (ii) Virginia fanpetals (*Sida hermaphrodita* Rusby L.) (SH); (iii) willow-leaf sunflower (*Helianthus salicifolius* A. Dietr) (HS) and (iv) giant miscanthus (*Miscanthus* × *giganteus* J.M.Greef & M.Deuter) (MG) comprised Factor A of the experiment.

Factor B was the form of fertilization: (i) wet digestate (WD); (ii) dry digestate (DD); (iii) torrefied digestate (TD); (iv) mineral fertilization (MF); (v) control treatment – no fertilization (C). Wet digestate (WD) was obtained from a pilot biogas plant at the Didactic and Research Station in Bałdy, owned by the University of Warmia and Mazury in Olsztyn. Dry digestate (DD) was obtained by thermal drying of the solid fraction from WD. Torrefied digestate (TD) was obtained by thermal torrefaction of DD. The contents of the main nutrients in each organic fertilizer were used to calculate their rates of use to achieve nitrogen fertilization at two rates: 85 and 170 kg ha^{-1} (Table 1). Mineral fertilization with NPK was balanced against organic fertilization, and the rates of mineral fertilization were subsequently decreased by 20% relative to organic fertilization. According to the Good Agricultural Practice Code for Poland (GAPC, 2004), the effectiveness of organic fertilization is close to 80% during the first year, so the rates of mineral fertilization were decreased by 20% compared with the macronutrients supplied with the organic fertilizers. Mineral NPK fertilizers were purchased and were applied as ammonium nitrate, triple superphosphate and potassium salt.

Factor C was the level of nitrogen (N) fertilization: (i) N 85 kg ha^{-1}; (ii) N 170 kg ha^{-1}. The upper dose of N application was calculated based on the GAPC, which allows a maximum of 170 kg ha^{-1} year^{-1} N. The lower dose was calculated as half of the upper nitrogen rate. The first dose of fertilizers in 2013 (85 kg ha^{-1} N) was applied before the experiment was set up in late April, whereas the second dose of fertilizers (another 85 kg ha^{-1} N) was applied as top dressing in early July 2013 in objects where the total nitrogen fertilization rate amounted to 170 kg ha^{-1} N. Nitrogen fertilization was applied in the following two years on a one-off basis regardless of the amount of nitrogen, before the growing season started, in late April 2014 and in early May 2015.

Three consecutive harvest cycles: (i) 2013; (ii) 2014 and (iii) 2015 years comprised Factor D, because of highly diverse intensity of PHC growth in the first years of cultivation.

2.2. Characteristics and preparation of the experiment site and conducting the experiment

The experimental plot was situated on a slightly configured land, with a slope not exceeding 2% with soil formed from sandy loam with a sandified surface layer. The content of the clay fraction in different genetic layers ranged from 6% in the humic horizon (0–0.26 m) to 24% in the 0.46–0.75 m layer. The humic horizon contained 2.65% of organic matter, which is equivalent to ca. 117.8 Mg ha^{-1}. The groundwater plate was below the level of 1.50 m. The soil pH and the content of P, K and Mg in different soil layers is shown in Table 2.

Triticale grown in rotation was the forecrop for the PHC. Roundup spraying was applied 5 dm^3 ha^{-1} after triticale was harvested. Subsequently, the field was disked after about three weeks. Winter ploughing at the depth of 0.30 m was performed in late autumn 2012. In spring (on late April 2013) the field was harrowed and Jerusalem artichoke tubers, Virginia fanpetals rhizomes, giant miscanthus rhizomes and herbaceous seedlings of willow-leaf sunflower were planted.

Jerusalem artichoke tubers and Virginia fanpetals rhizomes were planted at a density of 20 thousand ha^{-1}. Interrows were spaced every 0.75 m and the plants in a row were spaced every 0.67 m. There were 5 rows per plot, with 8 plants in a row, which gave 40 plants per plot. A plot was 3.75 m wide and 5.36 m long, i.e. its area was 20 m^2.

The giant miscanthus rhizomes and herbaceous seedlings of willow-leaf sunflower were planted at a density of 10 thousand ha^{-1}. Interrows were spaced every 1.0 m and the plants in a row were also spaced every 1.0 m. There were 4 rows per plot, with 6 plants in a row, which gave 24 plants per plot. A plot was 4.0 m wide and 6.0 m long, i.e. its area was 24 m^2. The whole experiment was set up in three replications, in the split-plot-split-block design and it included 120 plots.

Mechanical weeding was done three times during the first growing season 2013. In 2014 and 2015, soil in the interrows was loosened with a rototiller before liquid digestate was applied. On the plots where dry digestate, torrefied digestate and mineral fertilizers were applied, a rototiller was used after the fertilizers were spread. No chemical plant protection products were applied in the growing seasons of 2013–2015.

2.3. Above-ground biomass yield and laboratory analysis

The yield of the biomass of the above-ground parts of the plants was determined in late November 2013, 2014 and 2015 by cutting down all

Table 1
Amounts of organic and mineral fertilizers for plants, equivalent to the rate of N 85 and 170 kg ha^{-1} in consecutive years of cultivation.

Form of fertilization	Year of cultivation and level of N fertilization					
	2013		2014		2015	
	85	170	85	170	85	170
Wet digestate (1000 dm^3 ha^{-1})	32.69	65.38	21.79	43.59	23.61	47.22
Dry digestate (Mg ha^{-1})	6.85	13.70	3.04	6.07	6.20	12.40
Torrefied digestate (Mg ha^{-1})	5.55	11.11	4.07	8.13	7.14	14.28
Mineral fertilizers N; P; K (kg ha^{-1})	68.0;28.8;102.0	136.0;57.5; 204.0	68.0;22.7;62.8	136.0;45.4; 125.6	68.0;26.4;54.8	136.0;52.8; 109.6