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Energy efficiency of crops grown for biogas production in a large-scale farm in Poland

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ABSTRACT

This article presents the results of a 3-year field study into the yield and energy efficiency of maize, sweet sorghum, giant miscanthus, Amur silver grass, Virginia fanpetals and alfalfa with timothy grass grown in a farm in north-eastern Poland. The species with the highest DMY (dry matter yield) were the giant miscanthus (25.3 Mg ha^{-1} y^{-1}) and maize (22.7 Mg ha^{-1} y^{-1}). The production of 1 Mg of giant miscanthus DMY was least energy-intensive (0.74 GJ). In the remaining species, the energy inputs required to produce 1 Mg of DMY ranged from 1.12 to 1.40 GJ (maize, Amur silver grass, sweet sorghum) to 2.66 GJ (Virginia fanpetals). Giant miscanthus and maize were characterized by the highest energy outputs of 468 and 404 GJ ha^{-1} y^{-1}, respectively. The biomass of the remaining crops accumulated 31–68% less energy. In the climate of north-eastern Poland, the most energy-efficient crop was giant miscanthus (25.0), followed by maize (15.8), Amur silver grass (14.7) and sweet sorghum (12.5), whereas the lowest values of the energy efficiency ratio were noted in alfalfa with timothy grass (10.0) and Virginia fanpetals (7.0).

1. Introduction

Until recently, forests were the main source of energy crops in Poland [1]. In line with the latest trends, the agricultural sector is regarded as the major supplier of biomass for energy production. This concept is part of the European Bioeconomy in 2030 strategy which promotes the production and conversion of agricultural biomass into energy [2]. Sustainable production of agricultural biomass will play a key role in a bio-based economy [3]. The agricultural sector faces an immense challenge of catering to the growing demand for biomass without compromising food production [4]. In Poland, land is not farmed intensively, therefore, the yield of food crops can be significantly improved by introducing a minor increase in agricultural inputs and changing the production system. Land released from food production can be sown with energy crops [5]. The coexistence of food and energy crops can be achieved by limiting competition for farmland [6,7]. The area of agricultural land suitable for the production of energy crops in Poland is estimated at 0.9–1.0 million (M) ha, which accounts for around 5% of total farmland in the country [8]. According to the European Environment Agency [9], Poland can dedicate around 4 M ha of farmland to the production of energy crops in the coming decade. In Germany, where agricultural land spans a similar area to that noted in Poland, approximately 70% of renewable energy in 2012 was derived from biomass harvested from an area of approximately 2.5 M ha. The area of farmland suitable for the production of energy crops is estimated at 4 M ha [7].

Biomass production is a renewable process, and the CO_2 cycle is completed in nature within several months (annual plants) to several dozen years (perennial crops, woody plants) [10,11]. At present, bioenergy (electricity and/or heat) and biogas are the major bioproducts that can be derived from crops [12,13]. Biogas production is a key technology for the sustainable use of agricultural biomass as a renewable energy source [14]. Biogas can replace natural gas, and it can be used as fuel in transport. In Poland, biogas accounts for only 1.6% of energy from renewable sources [15]. Anaerobic digestion technology for methane production is a more efficient method of energy generation from biomass, compared

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with other biological and thermo-chemical conversion processes such as cellulosic ethanol [16]. Biomass constitutes abundant organic material that can be used for sustainable production of bioenergy and biofuels such as biogas (50–75% CH_4 and 25–50% CO_2) [17] and fertilizers containing plant-available minerals [18–20]. Anaerobic fermentation of biomass delivers environmental benefits by reducing natural methane emissions from self-decomposing biomass in waste dumps and open environments. In Europe, anaerobic fermentation processes were introduced already in the late 19th century for biogas production and biogas conversion to heat and electricity [15]. The conversion of organic matter, mainly animal slurry and organic wastes, to gaseous fuel on an industrial scale began only in the 1970s and 1980s, mainly in Germany and Denmark [21].

Agricultural biomass is a major substrate in European biogas plants. In Germany, the leading biogas supplier in Europe, around 45% of this fuel is produced from biomass [22]. The share of agricultural biomass in Poland's theoretical annual biogas output ranges from 13% [15] to 32% [1]. Biogas can be produced from various types of biomass. Nearly all types of organic substances of plant and animal origin can be fermented [1,15,17,19,23–27]. For this reason, the agricultural sector is regarded as the main supplier of biomass for energy generation [22]. However, according to Budzyński et al. [22] and Langeveld et al. [28], energy-dense biomass can be obtained only from dedicated plantations of high-yielding energy crops. At present, maize silage is the most popular substrate in biogas plants in Europe, and it accounts for 73% of plant substrates in German biogas plants [19]. Maize has a high share of crops in Europe [29], it is characterized by a high DMY (dry matter yield) (15–25 Mg ha^{-1} y^{-1}) [4,23,29–31], high biogas efficiency and stable fermentation [14,27,32]. Maize is a highly popular substrate for biogas production, but alternative energy crops have to be identified to guarantee sustainable crop rotation practices, food security and to counteract the increase in corn prices on global markets [25,27,33]. Maize production for energy generation should not lead to or justify monocultures which pose a direct threat to the biodiversity of agricultural ecosystems [7,25].

Perennial legumes, including alfalfa, red clover and fodder galega, have a high yield potential in Europe, which is estimated 7–23 Mg ha^{-1} y^{-1} DM (dry matter), subject to species and agricultural system [22,34]. Perennial legumes are less energy-intensive than other crops because they establish symbiotic relationships with bacteria that fix nitrogen from the air and, consequently, require less N fertilizers [23,35,36]. The biomass of perennial legumes (above-ground plant parts and roots) is also characterized by a relatively low C/N ratio [37], which contributes to rapid decomposition of organic matter by soil microorganisms [38]. Rapid decomposition limits periodic immobilization of N by microorganisms [39] and reduces the inhibitory effect of decomposition products on the emergence and early development of successive crops [40]. Grasses with the C_3 photosynthetic pathway, grown in single-species stands for crop rotation, are also characterized by a high biomass yield per unit area. Depending on species and agricultural system, their DMY ranges from 6 to 18 Mg ha^{-1} y^{-1} [11,29]. In Europe, C_3 grasses are often grown together with perennial legumes such as red clover and alfalfa, and their biomass yield is estimated at 9–26 Mg ha^{-1} y^{-1} DM [22,29]. Virginia fanpetals is also a valuable dicotyledonous plant whose yield after the 4th year ranges from 9 to 12 [31] to 14–20 Mg ha^{-1} y^{-1} DM [12,41,42]. Unlike legumes, Virginia fanpetals is not grown for food, therefore, the agricultural sector and the energy sector do not compete for its biomass [1].

In Europe, grass species with the C_4 photosynthetic pathway, including giant miscanthus, Amur silver grass and sweet sorghum, are characterized by a significantly higher biomass yield [11]. From the biological point of view, C_4 plants have the potential to out-yield plants with C_3 photosynthesis due to higher radiation, water and nitrogen-use efficiencies, but they require higher temperatures than C_3 plants to initiate growth in spring [10]. The DMY of giant miscanthus and Amur silver grass grown in plantations for more than 3–5 years is estimated at 10 to 38 [7,10,24,41,43,44] to 5–30 Mg ha^{-1} y^{-1} [41,45], respectively. Significant variations in their productivity can be attributed to high temperature requirements and, to a lesser extent, to agricultural inputs. According to Lewandowski et al. [10], the DMY of giant miscanthus was as high as 25 Mg ha^{-1} y^{-1} from the third year onwards in spring harvests between the latitudes of 37°N (southern Italy) and 50°N (central Germany). Yields above 30 Mg ha^{-1} y^{-1} DM are reported for locations in southern Europe with high annual incident global radiation and high average temperatures (e.g. 6200 MJ m^{-2} and 15.4 °C; data for southern Portugal), but only with irrigation. In central and northern Europe (Austria to Denmark), where global radiation and average temperatures are lower (e.g. 3500–3900 MJ m^{-2} and 7.3–8.0 °C; data for Denmark and Germany), yields without irrigation are more likely to reach 10–25 Mg ha^{-1} y^{-1} DM. The DMY of sweet sorghum ranges from 9 to 12 [31,33,41,45–47] to 23–26 Mg ha^{-1} y^{-1} [30,33].

The production of energy crops should be optimized to guarantee the highest energy efficiency [4,48–51]. The energy output of biomass harvested from 1 ha is as important as the energy inputs associated with the production (tillage, sowing, planting, fertilization, pest, disease and weed control, harvest) and transport of crops [4,50,51]. For this reason, species with a high biomass yield per unit area, in particular those characterized by a positive energy balance, i.e. higher energy outputs than energy inputs, are most suited for the generation of bioenergy [50,51]. The highest energy efficiency of biomass production can be achieved in perennial energy crops whose energy efficiency ratio, calculated as the ratio of the calorific value of biomass to total energy inputs, is several times higher than that of annual crops [4,52,53].

This paper presents the results of a macro-plot experiment carried out in a large-scale farm in north-eastern Poland. The biomass yield of annual (maize, sweet sorghum) and perennial (giant miscanthus, Virginia fanpetals, alfalfa with timothy grass) energy crops grown for biogas production, and the energy inputs associated with their production in a large-scale farm were determined by direct measurements. The aim of the study was to evaluate the suitability of selected agricultural crops for bioenergy generation. The working hypothesis states that maize, which is source of both food and energy, should not be grown in monoculture as the only crop for biogas production. Lignocellulosic grasses with the C_4 photosynthetic pathway (sweet sorghum, giant miscanthus, Amur silver grass) and dicotyledonous plants (Virginia fanpetals) were analyzed to identify species whose energy output is similar to that of maize. Alfalfa (dicotyledonous plant) with timothy grass (C_3 photosynthetic pathway) were selected as environmentally-friendly species with a high biomass yield and valuable components of agricultural ecosystems.

2. Materials and methods

2.1. Field experiment

A field experiment was carried out in 2010–2012 at the Agricultural Experiment Station in Bałcyny (53°35′46.4″ N, 19°51′19.5″ E, elevation 137 m) in north-eastern Poland. The station comprises 2000 ha of farmland, and it is owned by the University of Warmia and Mazury in Olsztyn. The experimental variables were annual and perennial plant species containing lignocellulose which is indispensable for biomass conversion to biogas. The annual plants