Abstract

Due to the current complicated political and economic situation, rapid fluctuations of fossil fuel prices and limitations of their availability as well as environmental issues, renewable energy sources (RES) will play a strategic role in energy supply. Biomass is the main type of RES in Poland and in the European Union (EU). Solid biomass used for energy generation is derived mainly from forests, the wood industry and agriculture. Moreover, perennial energy crops providing woody biomass (short rotation woody crops – SRWC), including black locust, poplar and willow, are an important source of this energy feedstock. SRWC biomass cultivation and production and an assessment of its quality as an energy feedstock is still a topical issue in many European countries as well as in the USA and in Canada. However, woody biomass derived from forests and from SRWC plantations, both in the primary form and as production waste, is a non-homogeneous fuel, which sometimes makes it a product of low attractiveness. Pelletization can substantially overcome these limitations, making solid biofuel in the form of pellets a more appealing and effective energy feedstock.

Global production of pellets has been growing steadily, increasing in 2021 by approximately 6.8% compared with 2020, with production in the EU increasing by 9%. In consequence, the demand for sawdust is growing while its availability is increasingly limited, and the prices are increasing, which, in turn, entails an increase in pellet production cost. This is why woody biomass from short-rotation woody crops (SRWC) may have to be used in pellet production to satisfy the demand for the raw material.

This doctoral dissertation is based on the findings of a field study of SRWC biomass production as part of the research conducted at the Department of Genetics, Plant Breeding and Bioresource Engineering, University of Warmia and Mazury in Olsztyn (UWM). Moreover, laboratory analyses of biofeedstock quality and studies of pellet production from agriculture-, forest-derived biomass and their mixtures were used in connection with an analysis of the costs and financial outlays for their production.

The main objective of the study was to evaluate the yield and usability of biomass derived from three SRWC species (black locust, poplar and willow) obtained in short harvest rotations for pellet production in mixtures with sawdust from forest trees (pine, birch). The specific objectives included the determination of **1.** The impact of (i) the species, (ii) soil enrichment method, and (iii) harvest rotation on the morphological features, survivability, yield and energy value of SRWC biomass during the 12 consecutive years of the cultivation. **2.** Thermophysical characteristics and elemental composition of SRWC biomass depending on

the factors mentioned above. **3.** Thermophysical characteristics and elemental composition of pellet produced from forest-derived biomass (pine, birch) and cultivated SRWC (black locust, poplar and willow) and from their mixtures. Moreover, the objective was to demonstrate which types of pellets met the parameters laid down in selected standards which categorize pellets into various classes. **4.** The cost and energy intensity of pellet production from forest wood and cultivated SRWC biomass and from their mixtures in various proportions (w/w).

Among the three SRWC species, poplar was the most stable with respect to plant survivability (mean 90.3%), and its plants were significantly taller (mean 7.09 m), with thicker shoots (mean 51.7 mm) than willow or black locust. Therefore, poplar produced a higher dry matter yield (mean 9.1 Mg ha^{-1} year^{-1} d.m.) and had a higher mean yield energy value. The yield of willow and black locust was lower by 6.5% and 47.5%, respectively. In general, the soil enrichment method applied in the study had a positive effect on the SRWC growth and, in consequence, on the biomass yield and its energy value compared with the control objects. The best effects were achieved in the variants with lignin used as one of the enriching agents, while the application of mineral fertilization or mycorrhizal inoculum alone and a combination of the two gave poorer results.

The SRWC species had the greatest impact on the biomass moisture, ash and nitrogen content, higher and lower heating value. The harvest rotation largely determined the biomass carbon, hydrogen and chlorine content. Black locust had the lowest moisture content (38.89%) and the highest lower heating value (10.25 GJ Mg^{-1}), sulfur (0.033% d.m.), nitrogen (0.91% d.m.) and chlorine (0.032% d.m.) content. Poplar had the highest mean higher heating value (19.84 GJ Mg^{-1} d.m.), moisture (56.52%), carbon (53.46% d.m.) and ash (1.67% d.m.) content. Willow had the lowest mean ash (1.25% d.m.), nitrogen (0.38% d.m.) and chlorine (0.19% d.m.) content and average moisture content.

This study confirmed that the production of pellets from a mixture of biomass from forest-derived wood and from an SRWC plantation is possible and justified. It was found that not only pellets from forest-derived sawdust (pine and birch) had good thermophysical properties and elemental composition but also that the addition of SRWC biomass (willow, poplar, black locust) to the sawdust allowed for the production of pellets which mostly met the requirements of the quality standards for pellets: ISO, PFI and KRFI. However, the quality of the pellet from biomass mixtures deteriorated (mainly with respect to the ash, nitrogen, sulfur and chlorine content) with an increasing share of SRWC biomass relative to forest-derived wood sawdust.

Due to the variation and contrast between SRWC biomass and forest-derived biomass, an addition of 25% of willow or poplar biomass to pine sawdust helped to maintain the quality features of the produced pellet at the highest level laid down in the quality standards. Referring solely to class A1 under ISO and Grade 1 according to KFRI, three types of pellets meet the criteria: (i) those made from pine wood, (ii) a combination of 75% pine and 25% willow (SP75+W25), and (iii) a combination of 75% pine and 25% poplar (SP75+P25).

The lowest cost (339.7 € Mg^{-1}) and energy input (1448 kWh Mg^{-1}) were determined for pellets produced from pine sawdust. The cost of pellet production from poplar and willow was 5-6% higher, respectively, and from black locust (by 8.5%) compared with pellet from pine. The energy input for pellet production from willow, black locust and poplar was higher by 48.1%, 50.4% and 53.2%, respectively. The cost of feedstock purchase (50.3–57.8%) and of the energy input for drying it (74.6–82.6%) accounted for definitely the largest portion of the costs and energy input. The energy efficiency index for pellet production from pine and birch sawdust (3.3–3.5) was higher than for SRWC (approximately 2.2). Nevertheless, an addition of 25% of SRWC biomass to sawdust was shown to help to produce pellets with an energy efficiency index exceeding 3.0. An increase in the share of SRWC biomass from 25% through 50% to 75% relative to pine and birch sawdust resulted in a cost and energy intensity increase and in the energy efficiency decrease for the pellets produced from those mixtures. Despite this, SRWC biomass can be included in the process of pellet production in mixtures with forest-derived woody biomass, as it is important for both pellet producers and end-users, especially given the rapid changes in the energy feedstock market and possible forest wood sawdust shortage.

Keywords: Black locust; Poplar; Willow; Pine; Birch; Woody biomass; Dendromass, Biomass yield; Harvest rotation; Energy value of yield; Thermophysical characteristics; Elemental composition; Moisture content; Ash content; Lower heating value; Willow pellet; Pine pellet; Agricultural pellet; Forest pellet; Pellet produced from biomass mixture; Pellet production costs; Energy intensity of pellet production; Efficiency of pellet production