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BIOENERGETIC ASSESMENT OF SWEET SORGHUM GROWN ON RECLAIMED LANDS

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Abstract: Sweet sorghum varieties of domestic breeding are the priority for studying their bioenergy potential, when they cultivated on reclaimed lands. Medove is a promising cultivar for growing on such sites in areas with insufficient water supply. The energetic characteristics of sorghum were studied on four types of mining substrates: loess-like loam (LLL), red-brown clay (RBC), green-grey clay (GGC), and piled up black soil mass (BS). Under such conditions, at the plots without fertilizer, Medove produced above-ground biomass from 38 to 82 ta ha^{-1}. The highest yield was recorded on loess-like loam. The sewage sludge application has promoted the increase of productivity by 4-44%. Although the sewage sludge introduction reduced the content of fermentable sugars in stem juice by 5.3-6.7% the theoretical ethanol yield was increased by 8-48%, except for the plot with loess-like loam. Thermal destruction of dry biomass proceeded in a similar way on all studied substrates. Nevertheless, it was revealed that the sewage sludge application shifts the process of thermolysis into the region of lower temperatures on BS and GGC, increases the stage of lignin decomposition on LLL, and affects the rates of the reactions, as well as slightly (LLL) and significantly (BS) augments the share of the incombustible residue.
Keywords: reclaimed lands, sweet sorghum, sewage sludge, biomass yield, conservative sugar yield, ethanol yield potential, kinetic characteristics of biomass

INTRODUCTION

Rapid depletion of natural resources and environmental degradation all over the world bring up the issue of creating environmentally friendly renewable energy sources. Biofuels are sustainable and renewable source of energy derived from organic matter in the form of biomass. In this connection, in recent decades, sorghum arouses particular interest as a multipurpose bioenergetic crop. The interest in sweet sorghum as an alternative energy crop is associated with the shortage and increase in the cost of non-renewable fossil energy products, and the use of ethanol as fuel (Rooney et al., 2007; Goff et al., 2010; Mathur et al., 2017).

Sweet sorghum belongs to the Sorghum bicolor (L.) Moench species, numerous cultivars and hybrids of which contain a large amount of fermentable sugars in stem juice. The ability of sweet sorghum to accumulate a lot of soluble sugars makes it a potential source of raw materials for the production of bioethanol. The biological features of this crop allow obtaining a good yield of green mass even on marginal lands and under insufficient water supply conditions. The most intense sugar in the stems accumulates after flowering. The maximum amount of sugars in plants is contained in the phase of wax and full ripeness of grain. The main components of extracted juice are sucrose, glucose, and fructose, which can be directly fermented into ethanol with efficiencies of more than 90% (Ratnavathi et al., 2010; Wu et al., 2010; Regassa & Wortmann, 2014). Lignocellulosic dry biomass can be used for the production of solid fuel (briquettes, granules) and for the making of biocomposite materials (Yu et al., 2012; Yin et al., 2013)

Due to its physiological traits and unique mechanism of moisture regulation, sorghum is highly resistant to soil and air drought, insects, diseases, salinity, and soil alkalinity (Reddy et al., 2007; Dalla Marta et al., 2014). In addition, this crop has one of the best rates of carbon assimilation (Prasad et al., 2007; Schmer et al., 2014).

Despite the unpretentiousness and resistance, if sorghum is grown on marginal lands, there is a risk of obtaining low yields due to the combined effect of multiple unfavorable factors. In this case it seems expedient to apply fertilizers. Given the current economic situation and the deficiency of mineral and organic fertilizers promising direction is the use composted sewage sludge in agriculture, fodder production, landscaping, for soil fertility restoration. Recently, the advantages and disadvantages of applying sewage sludge are widely discussed (Jamali et al., 2007; Wang et al., 2008; Singh & Agrawal, 2008; Hossain et al., 2010). Composted sewage sludge contains large amounts organic and inorganic elements essential to plants. Its effectiveness does not yielding to traditional organic and mineral fertilizers, but availability of potential toxic metals often restricts its uses. At the same time using sewage sludge which does not contain toxic impurities indicates a promising way of its use as a fertilizer.

MATERIAL AND METHOD

This study was carried out at Pokrov land reclamation station of Dnipro State Agrarian and Economic University which located in the Nikopol manganese ore deposit. The rocks of this ore basin are presented the holocene, postpliocene, neogen and paleogen deposits. These mining rocks are brought to the surface during process of manganese ore mining. The soil mass was taken off, piled up and heaped onto the land after the rock was replaced. Substrates formed in this way can be attributed to the category of Technosol which are soils strongly influenced by human activities, and as a result, their properties and pedogenesis are dominated by technical origin (De Kimpe & Morel, 2000).

Geographically, the land reclamation station is located in the Dnipropetrovsk region in the steppe zone of Ukraine with moderately continental climate: dry and hot summer and moderate winter. The average long-term air temperature is +8.5°C. The hottest month is July with the average temperature +22.0°C, the coldest is January with the average temperature -4.1°C. The site is located in the zone of unstable water supply with often prolonged droughts in the summer. The average hydrothermal coefficient is 0.9. In recent years, there has been a gradual increase in the average monthly air temperature with a simultaneous decrease in the amount of precipitation during the vegetation period. Seasonal precipitation and mean temperatures are shown in Figure 1.

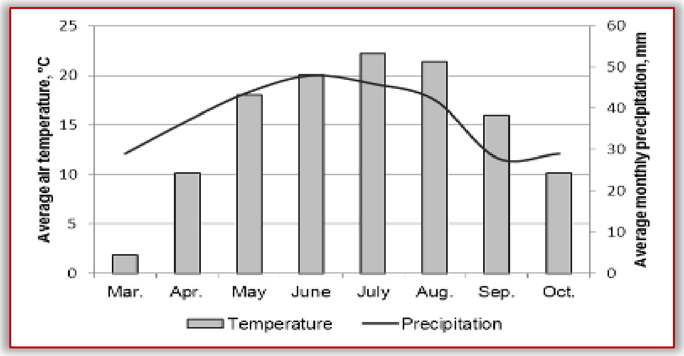

Figure1 - Average monthly temperature and precipitation amount at the reclamation station district (long-term data)

The sweet sorghum cultivar Medove was studied. This first generation hybrid was breeding at the Odessa Institute of genetics and breeding. This cultivar is mainly grown for silage and green mass, as well as for the sweet juice production and products of its processing (syrup, ethanol). Its potential productivity is 50-100 t ha^{-1}. The vegetative period before the milk-wax ripeness of grain is 90-100 days. The Medove is not affected by diseases and slightly damaged by aphids, resistant to lodging and is well suited for mechanized harvesting. Its main morphological characteristics are shown in Table 1.

Table 1. Morphological characteristics of sweet sorghum cultivar Medove

Height, cm	Number leaves per stem, pieces	Stem diameter, mm	Number stem per plant, pieces	Panicle form	Seed features
270-290	12-13	20-25	4-5	ellipsoid	brown, closed 3/4

The plants were sown on four types of mining substrates. Loess-like loam, (LLL), red-brown clay (RBC), and green-grey clay (GGC) were taken from the board of the quarry and exposed to long-term soil stabilization. Piled up black soil mass (BS) was taken in the soil stockpiling area. The humus content in these substrates is low (1.05- 1.25%), except black soil (3.29%). The ratio of humic and fulvic acids is 1.36 for BS and 0.62-0.69 for others substrates. The hygroscopic level varies from 7.6% (LLL) to 20.5% (GGC). To study the effect of sewage sludge, it was introduced into substrates in a dose of 30 ton ha^{-1}.

Biometric parameters, biomass productivity, brix, conservative sugar yield, theoretical ethanol yield, and dry biomass thermal characteristics were studied. The plant height was measured using a measuring line. To determine the yield of above-ground biomass, plants were harvested after the grain reached hard dough stage by cutting at the height of 10 cm from the ground level and weighed. After that, the biomass was dried to constant weight, and then weighed again. Brix was determined using a hand-held refractometer "RHBO–50ATC". Conservative sugar yield (t ha^{-1}) was calculated based on an approach assuming that the sugar concentration is 75% of Brix expressed in g kg^{-1} sugar juice (Wortmann et al., 2010; Ekefre et al., 2017).

Theoretical ethanol yield was calculated as sugar yield multiplied by a conversion factor: 0.58 L ethanol per kg of sugar (Rutto et al., 2013; Ekefre et al., 2017). The thermal analysis of plant biomass was carried out using the derivatograph Q-1500D of the "F. Paulik-J. Paulik-L. Erdey" system. Differential mass loss and heating effects were recorded. The results of the measurements were processed with the software package supplied with the device. Samples of biomass were analyzed dynamically at a heating rate of 10°C/min in an air atmosphere. The mass of samples was 100 mg. The reference substance was aluminum oxide. To handling the results obtained, the statistical analysis was applied using the StatGraphics Plus5 software package at significance level of 0.95 % (P-value < 0.05).

RESULTS

Cultivar Medove grown on mining substrates mainly conformed to the varietal characteristics. However, the plants grown on red brown clay, green-grey clay, and black soil were slightly lower (Table 2). Fresh biomass yield on these substrates was also lower than on loess-like loam. Thus, the lowest yield was recorded on green-grey clay (38.05±0.13 t ha^{-1}), and highest on loess-like loam (82.5±0.36 t ha^{-1}). The sewage sludge application on loess-like loam had no effect on biometric parameters and biomass yield. At the same time, the positive effect was observed on others substrates (Figure 2). The growth and productivity indicators have increased by 4-16% and by 14.5-44.5% respectively.

Table 2. Effect of the sewage sludge application on the height of cultivar Medove

	Black Soil	Loess-like loam	Red brown clay	Grey-green clay
Without fertilizer	255.2±3.03	295.3±4.92	250.1±1.15	235.3±1.99
With the sludge application	295.3±2.31	300.0±2.70	260.2±1.66	250.4±1.65

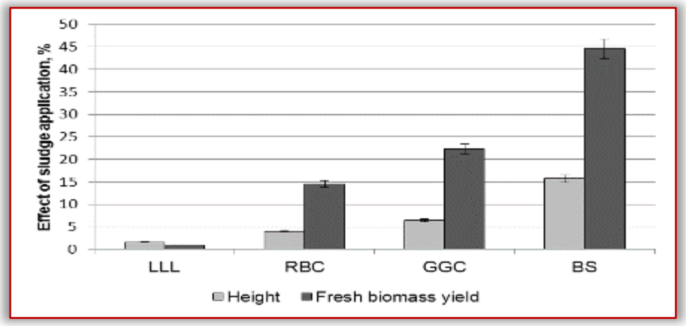

Figure 2 - Effect of sewage sludge application on growth and productivity of sorghum Medove grown on mining substrates

Due to the low biomass productivity on green-grey clay the conservative sugar yield was also small (2.75 t ha^{-1}). The highest yield was obtained on loess-like loam (5.91 t ha^{-1}). The same trend persisted in determining the theoretical ethanol yield, which was from 1611.4 L ha^{-1} to 3455.4 L ha^{-1}.

The sewage sludge introduction has reduced the content of fermentable sugars in stem juice by 5.3-6.7%, except plants grown on green-grey clay. Brix values on the plots without fertilizer varied between 19.0-19.3%, and on the plots with sludge application between 18.0-18.1%. Only on green-grey clay this index was 19.6%. Considering that in both variants on loess-like loam the amount of juice in the stems was practically the same, the yield of potential sugar and ethanol decreased by 4% in the version with the use of sewage sludge. On the other experimental plots, an increase in the theoretical ethanol yield was observed, especially on green-grey clay (Figure 3).

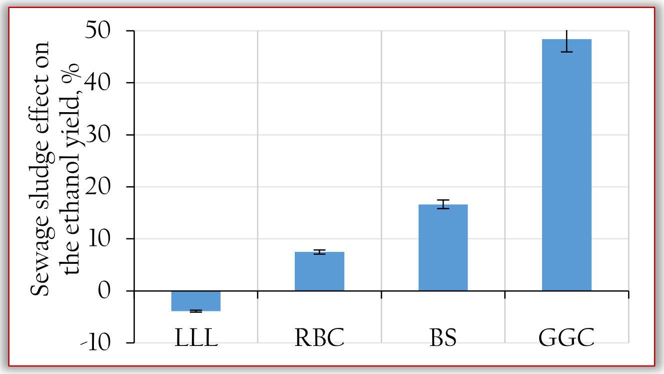

Figure 3 - Effect of sewage sludge application on theoretical ethanol yield of sorghum Medove grown on mining substrates

One of the most universal methods of treatment biomass for effective use as solid fuel is pyrolysis. Biomass is a highly reactive and thermally unstable raw material, so the low-temperature pyrolysis type is used for its processing (Fisher et al., 2002; Kumar et al., 2008). Conducted thermogravimetric analysis showed that thermolysis of Medove biomass passes in the temperature range from 30-40°C to 540-560°C. The water evaporation and the active removal of volatile components took place in the first stage within a temperature of 30-140°C (Table 3). The analysis of the rate of change in mass showed a single peak in this region. The mass loss was insignificant and varied within 5.2-8.6%.

In the second stage, the removal of volatile components was completed and the hemicellulose decomposition began. The mass loss was 13.6-14.2% (BS and LLL) and 17.4-19.6% (GGC and RBC). The highest rate of thermal reaction was observed at a temperature of 180-190°C. However, this rate was 14.0-14.4% / min for the samples taken on black soil and loess-like loam, and was almost twice as high on green-grey and red-brown clay (26.0%/min and 27.2%/min, respectively).

The main process of hemicellulose and cellulose decomposition was similar in all studied samples and took place in the temperature range 220-390°C (third stage). In this range, a small fraction of lignin decomposed as well. This phase was accompanied by the greatest mass loss (44.2-50.2%). The maximal rate of biomass destruction was 23.6-28.0%/min. During the last stage of thermolysis (390-560°C) thermal decomposition of cellulose and lignin was completed. In addition, the oxidation of formed at the previous stage char residue was occurred. At this stage, there were also no significant differences in the thermal behavior of biomass samples taken from different substrates. On the whole, the most complete combustion of biomass was observed on black soil.

The use of various amendments can affect the absorption of different elements from the soil and change the chemical composition of the biomass. This, in turn, can influence the process of thermal destruction. In our case, the sewage sludge application did not have any significant effect on the pyrolysis of sorghum biomass.

Nevertheless, some changes were noted in this process (Table 3, Figure 4). Thus, in the samples taken from black soil and green-grey clay, the first three stages of thermolysis passed in zones of lower temperatures. On loess-like loam the last stage was longer. Also, there were small variations in the rates at different stages of the biomass destruction. Moreover, on black soil the share of residual mass was 78% bigger than on the plot without fertilizer.

Table 3. Data of Medove biomass thermal degradation on mining substrates

Stage of biomass destruction	Temperature interval, °C		Mass loss, %		The share of residual mass, %	
	without fertilizer	with sludge application	without fertilizer	with sludge application	without fertilizer	with sludge application
Black soil						
I	40–140	30–120	8.6	6.0		
II	140–220	120–180	13.6	9.6		
III	220–380	180–360	47.4	50.8		
IV	380–550	360–550	24.0	22.2	8.8	11.4
Loess-like loam						
I	30–130	40–130	6.4	4.2		
II	130–210	130–210	14.2	19.0		
III	210–390	210–380	50.2	44.0		
IV	390–540	380–570	20.4	22.4	6.4	10.4
Red-brown clay						
I	30–130	50–140	5.2	4.0		
II	130–220	140–220	19.6	16.0		
III	220–390	220–370	44.2	43.2		
IV	390–560	370–570	22.6	28.8	8.4	8.0
Green-grey clay						
I	30–140	30–130	6.6	7.6		
II	140–220	130–200	17.4	13.8		
III	220–390	200–370	44.2	43.0		
IV	390–540	370–550	22.2	26.0	9.6	9.6

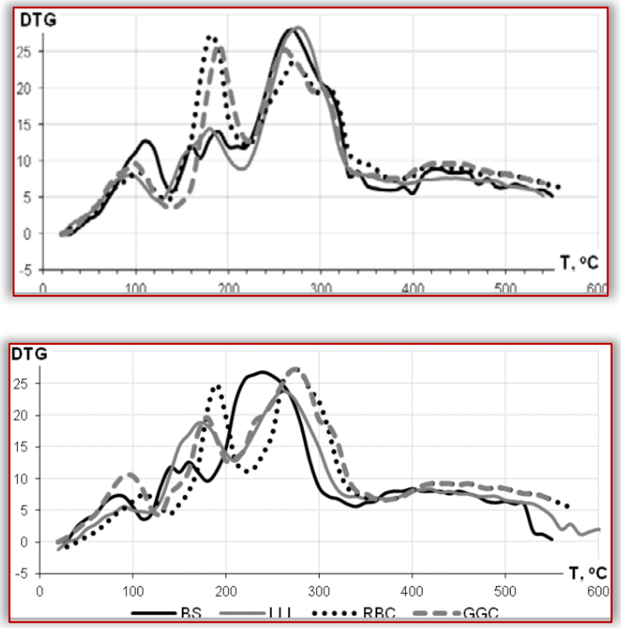

Figure 4 - DTG curves of biomass thermal destruction of sorghum cultivar Medove; variants without fertilizer (up) and with sewage sludge application (below).

CONCLUSIONS

Medove is a promising cultivar of sweet sorghum for growing on mining lands in areas of insufficient water supply. Under such conditions it can produce above-ground biomass from 38 to 82 ta ha^{-1}. The sewage sludge application can promote increase of productivity by 4-44%. Although the sewage sludge introduction reduced the content of fermentable sugars in stem juice by 5.3-6.7% the theoretical ethanol yield was increased by 8-48%, except for the plot with loess-like loam.

Thermal destruction of dry biomass proceeded in a similar way on all studied substrates. It was revealed that the sewage sludge application shifts the process of thermolysis into the region of lower temperatures (for BS and GGC), increases the stage of lignin decomposition (for LLL), and affects the rates of the reactions, as well as slightly (LLL) and significantly (BS) augments the share of the incombustible residue.

Note:
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