

## Prospects for the Cultivation and Utilization of Switchgrass (*Panicum virgatum*) in Moldova

Victor Țiței

“Alexandru Ciubotaru” National Botanical Garden (Institute) of Moldova State University,  
18 Pădurii Street, MD 2002, Chișinău, Republic of Moldova

\*Corresponding author. E-mail: vic.titei@gmail.com; victor.titei@gb.usm.md

### ABSTRACT

The goal of this research was to evaluate the productivity and quality indices of phytomass obtained from switchgrass (*Panicum virgatum*) genotypes grown in the experimental plot of the National Botanical Garden (Institute) of MSU, Chișinău, Republic of Moldova, for use as forage and as feedstock for biomethane production. The productivity of the studied switchgrass genotypes ranged from 3.85 to 4.45 kg/m<sup>2</sup> fresh biomass or 1.41 to 1.75 kg/m<sup>2</sup> dry matter. The analysis of the biochemical composition suggested that the dry matter of the whole plants harvested at the middle flowering stage contained 61-68 g/kg CP, 412-419 g/kg CF, 422-433 g/kg ADF, 653-692 g/kg NDF, 49-52 g/kg ADL, 231-259 g/kg HC, 373-381 g/kg Cel, 82-93 g/kg ash. The nutritive and energy value of switchgrass fresh forage was 52.2-56.0% DDM, 9.04-9.06 MJ/kg ME and 5.05-5.018 MJ/kg NEL. The prepared hays had 56-65 g/kg CP, 79-100 g/kg ash, 414-420 g/kg CF, 52-57 g/kg ADL, 374-384 g/kg Cel, 253-272 g/kg HC, 109-113 g/kg TSS, with 54.5-55.7% DDM, RFV= 71-76, 10.89-11.19 MJ/kg DE, 8.94-9.12 MJ/kg ME and 4.96-5.14 MJ/kg NEL. The quality of silages dry matter was: 6.2-7.0% CP, 8.2-9.9% ash, 39.9-41.4% CF, 39.1-42.3% ADF, 63.2-65.7% NDF, 4.1-4.3% ADL, 35.0-38.0% Cel, 23.4-24.1% HC, 2.1-4.9% TSS, 559-578 g/kg DDM, RFV=79-85, 11.14-11.48 MJ/kg DE, 9.15-9.43 MJ/kg ME and 5.17-5.45 MJ/kg NEL. The biochemical methane potential of switchgrass substrates varied from 302 to 331 l/kg VS.

**Keywords:** biochemical composition, biochemical methane potential, forage quality, *Panicum virgatum* genotypes, productivity.

### INTRODUCTION

*Panicum* L. is a genus in the family Poaceae comprising approximately 450 species of annual and perennial grasses. These species range from weedy forms to economically important cultivated crops used as fodder, grain, and ornamentals. Species of *Panicum* are widely distributed in tropical and warm temperate regions and are characterized by a high tolerance to soil salinity and a more efficient use of water and nutrients compared with many other members of the Poaceae family. Many representatives of this genus are popular agricultural and horticultural crops. One of the most commonly cultivated *Panicum* species as grain and forage crops is proso millet *Panicum miliaceum* and has also been studied, breeding and cultivated in our region (Pricop, 2003; Kertikov and Kertikova, 2016; Kwiatkowski et al., 2017; Petcu et al., 2024; Țiței, 2025).

*Panicum virgatum* L., commonly known as switchgrass, is native to North America and is the most abundant in the Great Plains and eastern states of US. It is a warm-season, perennial, rhizomatous grass that utilizes C<sub>4</sub> photosynthesis and may occasionally form a knotty crown. The stems are green to purple, erect or decumbent, 40-300 cm tall and 3-5 mm in diameter and form dense clumps. Ligules are 2-6 mm long, and the leaf blades are flat and erect, measuring 30-60 cm in length and 2-15 mm in width. The adaxial leaf surfaces are sometimes densely pubescent, with scabrous margins and a prominent midrib. The inflorescence is an open panicle, 10-55 cm long and 4-20 cm wide, with thin, straight primary branches. Spikelets are 2.5-8 mm long and 1.2-2.5 mm wide, narrowly lanceolate, turgid to slightly laterally compressed, glabrous and acuminate. Seeds are 3-6 mm long and 1.2-1.5 mm wide, developed from a single-flowered spikelet.

Switchgrass typically produces seeds abundantly, with average seed yields in cultivated stands ranging from 500 to 700 kg/ha. Switchgrass reproduces both generatively by seeds and vegetatively by rhizomes. The root system can reach depths of 3 m or more.

*Panicum virgatum* has traditionally been classified into two major ecotypes: upland and lowland, based on phenotypic differences resulting from latitudinal adaptation. Lowland ecotypes are typically taller, with fewer but larger tillers, broader and longer leaf blades, and thicker stems. These plants are better adapted to longer growing seasons and are less tolerant of cold temperatures compared to upland ecotypes. Recently, a third coastal ecotype has been identified, which combines the leaf characteristics of upland ecotypes with the plant architecture of lowland types, occupying similar ranges (Casler, 2012; Liu et al., 2022; Razar et al., 2022). Switchgrass productivity is influenced by several factors, including genotype, growing season, length, stand maturity, soil quality and the availability of water and nutrients. *Panicum virgatum* can thrive in a wide range of soil types and textures, with pH levels ranging from 4.5 to 7.6. It is tolerant of moderate soil salinity and acidity, making it suitable for various revegetation and erosion control projects. Switchgrass is well-suited for planting on marginal lands that are unsuitable for grain and forage crops and requires relatively low inputs of chemical fertilizers. Due to these characteristics, it holds significant potential as a sustainable bioenergy crop. *Currently, Panicum virgatum is being actively studied, introduced and explored as a forage and bioenergy crop in various regions around the world* (Belanger et al., 2012; Butkutė et al., 2013; Rakhmetova et al., 2014, 2020; Richner et al., 2014; Zheng et al., 2015; Seepaul et al., 2016; Milenkovic et al., 2018; Ashworth et al., 2020; Başar et al., 2020; Griffiths et al., 2022; Kupryś-Caruk et al., 2023; Tóth et al., 2023; Norkeviciene et al., 2025).

The aim of this research was to evaluate the productivity and quality indices of

phytomass from *Panicum virgatum* genotypes introduced in Republic of Moldova.

## MATERIAL AND METHODS

The study focused on two switchgrass genotypes of *Panicum virgatum*: one without anthocyanin pigmentation (green) and the other with anthocyanin pigmentation (purple), both of which were grown at the experimental plot of the “Alexandru Ciubotaru” National Botanical Garden (Institute) of MSU, in Chişinău.

Plant samples of *Panicum virgatum* were harvested at the middle flowering stage during their second year of growth. The plants were chopped into 1.5-2.0 cm pieces using a laboratory forage chopper, and the dry matter content was determined by drying the samples to a constant weight at 105°C. Silage was made from the chopped green mass, which was packed into sealed glass containers and stored at ambient temperature (18-20°C). After 45 days, the containers were opened, and the sensory and fermentation indices of the silage were evaluated following standard laboratory procedures, as outlined in the Moldovan standard SM 108\*. Hay was dried directly in the field. For biochemical analysis, plant samples were dried in a forced-air oven at 60°C, then milled in a beater mill with a 1 mm sieve. Several key biochemical parameters, including crude protein (CP), ash, acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL), total soluble sugars (TSS), digestible dry matter (DDM), and digestible organic matter (DOM), were analyzed using the PERTEN DA 7200 near-infrared spectroscopy (NIRS) technique. Additionally, the concentrations of hemicellulose (HC), cellulose (Cel), digestible energy (DE), metabolizable energy (ME), net energy for lactation (NEL), and relative feed value (RFV) were calculated following standard methods.

The carbon content of the substrates was determined using an empirical equation based on Badger et al. (1979), while the biochemical methane potential was calculated according to

the equations provided by Dandikas et al. (2015).

## RESULTS AND DISCUSSION

The analysis of the biological characteristics of the studied *Panicum virgatum* genotypes (Table 1) revealed that the productivity of the switchgrass genotypes ranged from 3.85 to 4.45 kg/m<sup>2</sup> of fresh mass, or 1.41 to 1.75 kg/m<sup>2</sup> of dry matter. The leaf and panicle content in the natural forage was on average 42-44%. The purple *Panicum virgatum* genotype, at the middle flowering stage, exhibited a shorter plant height, which negatively impacted its productivity.

Several studies have documented the productivity of *Panicum virgatum*. Belanger et al. (2012) reported that the forage dry matter yield of *Panicum virgatum* ranged from 9.0 t/ha in late July to 11.59 t/ha in early September. Grigatti et al. (2012) observed that the crop dry biomass yield for switchgrass was 22.4 t/ha, compared to 27.8 t/ha for maize and 20.8-29.2 t/ha for sorghum. Rakhmetov et al. (2014) found that the yield of a local switchgrass cultivar reached 70.19 t/ha of fresh mass. Barbanti et al. (2014) reported that switchgrass biomass yield was 52.6 t/ha of fresh mass, or 22.4 t/ha of dry matter. Mantino et al. (2015) observed that, in Pisa, Italy, the productivity of a pure switchgrass stand ranged from 8.9 to 9.8 t/ha of dry matter, while a mixture with alfalfa yielded 10.0-11.8 t/ha of dry matter. Rakhmetova et al. (2020) found that, in the

first week of August, breeding lines and varieties of *Panicum virgatum* reached a height of 150-180 cm, with productivity ranging from 41.35 to 64.16 t/ha of fresh mass (or 11.28-15.84 t/ha of dry matter). The aboveground mass structure was composed of 39.0-44.8% leaves, 38.8-39.9% stems and 16.7-21.5% inflorescences. Finally, a study by Norkeviciene et al. (2025) conducted under the climatic conditions of Lithuania found that the dry matter yield of the switchgrass cultivar 'Dacotah' ranged from 5.9 to 6.7 t/ha, 'Forestburg' ranged from 5.3 to 9.5 t/ha, and 'Cave in Rock' ranged from 6.7 to 11.3 t/ha.

The biochemical composition and the nutritive value of the green mass harvested from *Panicum virgatum* genotypes is presented in Table 2. The analysis of the biochemical composition suggested that the dry matter of the switchgrass whole plants harvested in middle flowering stage contained 61-68 g/kg CP, 412-419 g/kg CF, 422-433g/kg ADF, 653-692 g/kg NDF, 49-52 g/kg ADL, 231-259g/kg HC, 373-381 g/kg Cel, 124-127 g/kg TSS and 82-93 g/kg ash. The green fodder from the purple genotype of switchgrass is characterized by higher cell wall content and lower concentration of crude protein and minerals. The concentration of total soluble sugars of the studied *Panicum virgatum* genotypes does not differ essentially. The nutritive and energy value of switchgrass fresh forage was 55.2-56.0% DDM, 9.04-9.06 MJ/kg ME and 5.05-5.18 MJ/kg NEI.

Table 1. Some agrobiological peculiarities of the studied *Panicum virgatum* genotypes

Genotypes	Plant height, cm	Yield, kg/m <sup>2</sup>		Content of leaves and panicles in fodder, %
		fresh mass	dry matter	
<i>Panicum virgatum</i> (purple)	127	3.85	1.41	42.0
<i>Panicum virgatum</i> (green)	144	4.45	1.75	44.0

Table 2. The biochemical composition and the nutritive value of the fresh mass harvested from *Panicum virgatum* genotypes

Indices	<i>Panicum virgatum</i> (purple)	<i>Panicum virgatum</i> (green)
Crude protein, g/kg DM	61	68
Crude fibre, g/kg DM	419	412
Minerals, g/kg DM	82	93
Acid detergent fibre, g/kg DM	433	422
Neutral detergent fibre, g/kg DM	692	653
Acid detergent lignin, g/kg DM	52	49
Cellulose, g/kg DM	381	373
Hemicellulose, g/kg DM	259	231
Total soluble sugars	127	124
Digestible dry matter, g/kg DM	552	560
Relative feed value	74	92
Digestible energy, MJ/ kg DM	11.01	11.86
Metabolizable energy, MJ/ kg DM	9.04	9.06
Net energy for lactation, MJ/ kg DM	5.05	5.18

Various studies have reported different results regarding the nutrient content of whole plants from *Panicum* species. According to Griffin and Jung (1983), the forage quality of *Panicum virgatum* leaf mass harvested at the early heading stage was 8.5% CP, 67.1% NDF, 4.7% lignin and 58.8% IVDMD, while the stem mass had 3.8% CP, 77.7% NDF, 8.3% lignin and 47.2% IVDMD. Ferri et al. (2000) reported that *Panicum virgatum* hay contained 749 g/kg dry matter (DM) with 1.3% CP, 5.3% ash, 85.9% NDF, 54.3% ADF, 5.6% Klason lignin and 33.6% *in vivo* dry matter apparent digestibility. Dien et al. (2006) found that switchgrass harvested at the pre-boot stage had 6.5% CP, 1.0% EE, 8.9% ash, 66.9% NDF, 1.2% ADL, 33.7% Cel, 31.8% HC and 18.22 MJ/kg GE, while plants harvested at anthesis stage contained 3.2% CP, 1.0% EE, 5.7% ash, 66.9% NDF, 2.3% ADL, 34.0% Cel, 30.1% HC and 18.61 MJ/kg GE. Pilat et al. (2007) remarked that the green forage dry matter from switchgrass harvested in different stages of vegetation contained 231.7-313.3 g/kg DM with 92.70-94.83% OM, 5.53-14.14% CP, 1.32-1.86% CT, 31.52-39.58% CF, 65.13-74.80% NDF, 33.26-42.74% ADF, 31.51-32.93% HC and 42.94-48.23% NFE. According to Jefferson and McCaughey (2012), the forage dry matter

from *Panicum virgatum* cultivars contained 53.7-64.7% NDF, 28.2-33.0% Cel, 26.2-30.2% HC with 44.3-61.2% OMD. Guretzky et al. (2011) observed that switchgrass had 8.5-10.5 N g/kg, 261-381 g/kg CF, 426-455 g/kg ADF, 740-752 g/kg NDF and 411-492 g/kg IVDMD. Belanger et al. (2012) found that the forage characteristics of switchgrass harvested in late July were 68.0% NDF, 38.3% ADF, 4.02% soluble carbohydrates and 721 g/kg IVTD. In contrast, switchgrass forage harvested in early September had 67.7% NDF, 39.4% ADF, 7.51% soluble carbohydrates, and 649 g/kg IVTD. Barbanti et al. (2014) reported that switchgrass biomass contained 2.38% CP, 0.96% EE, 3.99% soluble sugars, 0.54% starch, 28.3% Cel and 23.5% HC. Richner et al. (2014) reported that the nutritive values of switchgrass mowed at the post-anthesis stage ranged from 7-11% CP, 65-69% NDF, 33-38% ADF, 5-8% ADL and 58-73% IVTD. Mantino et al. (2015) found that the quality indices of switchgrass green mass were 5.2% CP, 77.0% NDF, 43.0% ADF and 5.6% ADL. Gelley et al. (2016) reported that switchgrass mowed in June had 11.3% CP, 63.2% NDF and 41.4% ADF. Seepaul et al. (2016) noted that whole-plant switchgrass harvested during the June-July period contained 3.5-4.6% CP, 6.5-7.7% ash, 73.9-

80.5% NDF, 40.4-45.9% ADF, 4.6-7.9% ADL, 33.5-35.1% Cel, 32.9-40.9% HC, and 553-589 g/kg IVDMD. Vergun et al. (2018) mentioned that plant raw material collected in the period of anthesis from investigated cultivar and varieties of *Panicum virgatum* contained 340.5-482.1 g/kg DM with 1.88-4.63% ash, 4.11-10.49% total sugars, 2.68-5.92% monosaccharides, 14.39-79.50 mg% ascorbic acid, 0.277-1.407 mg% carotene and gross energy value 3588.18-3719.22 cal/g. Mantino et al. (2017) mentioned that the quality indices of switchgrass forage harvested in boot stage in the first week of July was 2.8-3.0% CP, 73.7-73.9% NDF, 38.6-39.0% ADF, 5.8-6.2% ADL, 0.8-0.9% EE, 18.1-18.2% NSC, 4.2-4.9% ash. Milenkovic et al. (2018) reported that the biomass quality of the 14 switchgrass genotypes studied ranged from 6.67 to 8.92% ash, 5.62-8.84% CP, 1.47-2.90% EE, 31.79-36.79% Cel, 67.02-73.15% NDF, 36.05-44.07% ADF, and 39.08-44.29% NFE. Amaleviciute-Volunge et al. (2020) found that the chemical composition of *Panicum virgatum* biomass was 5.80% ash, 8.70% CP, 70.49% NDF, 39.9% ADF, 5.70% ADL, 5.91% WSC, 34.2% Cel, 30.54% HC with 46.8% digestibility, while *Medicago sativa* biomass 9.17% ash, 20.93% CP, 37.38% NDF, 35.3% ADF, 10.9% ADL, 11.1% WSC, 24.4% Cel, 2.07% HC with 45.8% digestibility. Ashworth et al. (2020) remarked that switchgrass harvested in the June had 5.7-7.8% CP, 6.5-7.7% ash, 63.1-67.9% NDF, 34.3-34.9% ADF, 527-535 g/kg TDN. Başar et al. (2020) mentioned that switchgrass varieties contained 6.00-9.43% soluble protein, 34.76-36.24% HC, 33.13-35.94% Cel, 5.42-5.57% lignin, 14.1-16.4% total sugar. Głowacka et al. (2020) reported that the quality indices of the green mass from *Panicum virgatum* plants were 5.50-6.59% ash, 8.03-10.62% CP, 34.66-35.25% CF, 66.63-70.31% NDF, 39.04-40.06% ADF, 4.64-5.05% lignin, 32.73-34.33% Cel, 27.08-30.25% HC. Tang et al. (2020) stated that, depending on nutrient levels and fertilizer doses, the *Panicum virgatum* forage had 3.92-5.55% CP, 57.1-64.0% NDF, 32.9-35.1% ADF, 7.18-8.8% soluble sugars,

29.46-32.02% Cel, 24.21-29.02% HC, 5.0-8.21% ash, 61.6-63.2% DDM, 1.38-1.44 Mcal/kg NEI and RFV=89.5-103.2. Kieffer et al. (2023) reported that *Panicum virgatum* biomass exhibited the following quality indices: 3.65% ash, 6.72% CP, 74.60% NDF, 42.88% ADF, 4.06% lignin, 38.97% Cel, 31.73% HC, 3.76 g/kg Ca and 1.75 g/kg P, and a relative feed value (RVF) of 69.84. Kupryś-Caruk et al. (2023) reported that dry matter of switchgrass fresh mass contained 10.2% CP, 34.5% Cel, 23.1% HC, 5.1% lignin and 5.4% WSC. Tóth et al. (2023) mentioned that *switchgrass biomass depending on the cultivar, nutrition, and climatic conditions of a specific year, contained 59.20-81.15% NDF, 30.15-50.91% ADF, 6.02-12.41% ADL, 17.98-40.08% Cel and 21.34-38.41% HC*. Norkeviciene et al. (2025) found that the first cut dry matter of the studied *Panicum virgatum* cultivars, in mid-summer, contained 1.02-1.03% N, 48.1-48.2% C, 67.9-69.7% NDF, 38.4-41.8% ADF, 6.15-7.97% ADL, 8.05-9.17% WSC, 4.91-5.23% starch, 33.4-35.6% Cel, 27.9-29.4% HC, while switchgrass samples in harvested in early August contained 0.71-0.78% N, 48.6-48.8% C, 73.4-74.5% NDF, 44.0-45.5% ADF, 7.43-8.33% ADL, 7.25-9.50% WSC, 8.07-9.95% starch, 36.6-37.2% Cel, and 28.8-29.6% HC, respectively.

Hay is a fundamental forage for many herbivores, providing essential fiber, nutrients, and roughage to ruminants (e.g., cattle, sheep, and goats), horses, and small animals such as rabbits and guinea pigs, particularly when fresh pasture is unavailable. It supports digestion and dental health. Hay is produced by drying grasses and legumes, serving as a vital food source during lean seasons. The nutrient content and energy value of hay prepared from *Panicum virgatum* are shown in Table 3. We found that the prepared hays contained 56-65 g/kg CP, 79-100 g/kg ash, 414-420 g/kg CF, 52-57 g/kg ADL, 374-384 g/kg Cel, 253-272 g/kg HC, 109-113 g/kg TSS, with 54.5-55.7% DDM, RFV=71-76, 10.89-11.19 MJ/kg DE, 8.94-9.12 MJ/kg ME and 4.96-5.14 MJ/kg NEI. The hay from the purple genotype of switchgrass is characterized by higher

concentration of cell wall fractions (NDF, ADF, ADL) and lower amount of crude protein, minerals and energy concentration

Several literature sources described the quality indices of the hay prepared from *Panicum* species. According to Ferri et al. (2000), the hay from *Panicum virgatum* 'Alamo' had 749 g/kg DM with 5.3% ash, 13% CP, 85.8% NDF, 54.3% ADF and 336 g/kg IVDMD. Burns et al. (2014) mentioned that *Panicum virgatum* hay prepared in middle June had 9.9% CP, 72.6%

NDF, 38.0% ADF, 5.2% lignin, 31.9% Cel, 34.5% HC with 44.0% IVDMD, but the hay prepared in early July contained 6.7% CP, 73.5% NDF, 39.7% ADF, 5.7% lignin, 32.8% Cel, 33.8% HC, with 45.5% IVDMD, respectively. Davis et al. (2018) mentioned that the hay prepared from *Panicum virgatum* cultivars, harvested at different stages of maturity, contained 901-912 g/kg DM with 4.8-13.5% CP, 57.1-65.1% NDF, 29.2-36.7% ADF, 51.50-72.6% DMD.

Table 3. The biochemical composition and the nutritive value of the hay from studied *Panicum virgatum* genotypes

Indices	<i>Panicum virgatum</i> (purple)	<i>Panicum virgatum</i> (green)
Crude protein, g/kg DM	56	65
Crude fibre, g/kg DM	420	414
Minerals, g/kg DM	79	100
Acid detergent fibre, g/kg DM	441	426
Neutral detergent fibre, g/kg DM	713	679
Acid detergent lignin, g/kg DM	57	52
Cellulose, g/kg DM	384	374
Hemicellulose, g/kg DM	272	253
Total soluble sugars	109	113
Digestible dry matter, g/kg DM	545	557
Relative feed value	71	76
Digestible energy, MJ/ kg DM	10.89	11.10
Metabolizable energy, MJ/ kg DM	8.94	9.12
Net energy for lactation, MJ/ kg DM	4.96	5.14

Silage is a crucial feed for farm animals, preserving nutrients from fresh forage in a highly digestible, palatable, and cost-effective form. It is especially vital during periods when fresh forage is scarce, improving animal health and productivity (e.g., milk production, weight gain), while reducing reliance on expensive concentrates by providing essential energy and fiber.

When opening the glass containers with ensiled switchgrass, there was no gas or liquid leakage from the preserved mass. The prepared switchgrass silage had a homogeneous, agreeable olive color and a pleasant smell typical of grass silage, without any mold or mucus. The silage prepared from different switchgrass genotypes, Table 4, had a pH ranging from 4.14 to 4.26, with organic

acid concentrations of 30.6-34.7 g/kg, of which 90-93% was lactic acid. The nutrient concentration of silages dry matter was: 6.2-7.0% CP, 8.2-9.9% ash, 39.9-41.4% CF, 39.1-42.3% ADF, 63.2-65.7% NDF, 4.1-4.3% ADL, 35.0-38.0% Cel, 23.4-24.1% HC, 2.1-4.9% TSS, 559-578 g/kg DDM, RFV=79-85, 11.14-11.48 MJ/kg DE, 9.15-9.43 MJ/kg ME and 5.17-5.45 MJ/kg NEI.

It was found that silage from purple switchgrass genotype is characterized by higher concentration of crude protein, minerals, hemicellulose and lower level of acid detergent lignin and cellulose, which had a positive impact on the digestibility and nutritive energy value, as compared with the silage from the green genotype of switchgrass.

Table 4. The biochemical composition and the nutritive value of the silage from studied *Panicum virgatum* genotypes

Indices	<i>Panicum virgatum</i> (purple)	<i>Panicum virgatum</i> (green)
pH index	4.14	4.26
Organic acids, g/kg DM	30.6	34.7
Crude protein, g/kg DM	62	70
Crude fibre, g/kg DM	414	399
Minerals, g/kg DM	82	99
Acid detergent fibre, g/kg DM	423	391
Neutral detergent fibre, g/kg DM	657	632
Acid detergent lignin, g/kg DM	43	41
Cellulose, g/kg DM	380	350
Hemicellulose, g/kg DM	234	241
Total soluble sugars	21	49
Digestible dry matter, g/kg DM	559	578
Relative feed value	79	85
Digestible energy, MJ/ kg DM	11.14	11.48
Metabolizable energy, MJ/ kg DM	9.15	9.43
Net energy for lactation, MJ/ kg DM	5.17	5.45

Some authors mentioned various findings about the quality of the silage prepared from *Panicum* species. Pilat et al. (2007) reported that switchgrass silage without supplement is characterized by pH=4.57, 1.19% lactic acid, 0.71% acetic acid, 0.08% butyric acid, 240.4 g/kg DM with 91.61% OM, 11.84% CP, 2.99% CT, 33.91% CF, 74.57% NDF, 43.22% ADF, 31.35% HC, 42.87% NFE, while silage with supplements pH=4.31-4.60, 1.25-1.25% lactic acid, 0.65-0.73% acetic acid, 0-0.06% butyric acid, 238.8-254.4 g/kg DM, 91.49-92.14% OM, 11.45-12.64% CP, 2.42- 2.96% CT, 33.62-35.76% CF, 70.30-71.72% NDF, 39.24-41.01% ADF, 30.26-31.06% HC and 40.22-40.29% NFE. Belanger et al. (2012) mentioned that the characteristics of switchgrass silage prepared in late July were the following: pH=4.36, 4.45% lactic acid, 0.77% acetic acid, 1.32% nitrogen, 0.61% soluble carbohydrates, 0.65% starch, while the switchgrass silage prepared in early September - pH=4.0, 4.36% lactic acid, 0.33% acetic acid, 1.32% nitrogen, 1.03% soluble carbohydrates, 1.11% starch. According to Eliş and Özyazıcı (2019), the silage obtained from switchgrass cultivars had pH=3.84-4.73, and contained 390-510 g/kg dry matter with 1.78-2.35%

lactic acid, 0.35-1.55% acetic acid, 0.05-0.33% butyric acid, 3.76-5.33% CP, 70.96-75.41% NDF, 39.30-41.73% ADF, 18.75% TSS, 35.13% HC, 10.44% ash. Kupryś-Caruk et al. (2023) remarked that the silage prepared from switchgrass fresh mass was characterized by pH=5.4, 1.31% lactic acid, 7.0% acetic acid, 0.08% butyric acid, 8.2% CP, 34.9% Cel, 23.6% HC, 5.6% lignin and 0.04% WSC, but switchgrass silage prepared with inoculant addition pH=5.3, 0.93% lactic acid, 15.7% acetic acid, 0.02% butyric 7.8% CP, 32.5% Cel, 22.8% HC, 5.0% lignin and 0.1% WSC. Norkeviciene et al. (2025) mentioned that the silage from studied *Panicum virgatum* cultivars harvested in mid-July was characterized by the following indices: pH=4.0-4.2, 319-328 g/kg dry matter with 94.1-94.7% VS, while the silage prepared in early August had pH=4.4-5.1, 345-424 g/kg dry matter with 94.8-94.9% VS.

In recent years, the use of C<sub>4</sub> grass species, as biomass feedstock for renewable energy production has gained significant attention, especially for biomethane generation. Biogas, which includes biomethane, is produced through the anaerobic digestion of organic matter. This fermentation process is dynamic

and depends on various factors, including the carbohydrate content, nitrogen compounds, lignin concentration, biodegradability, and the carbon-to-nitrogen (C/N) ratio of the substrate. The biochemical characteristics and biomethane production potential of different *Panicum virgatum* genotypes were assessed (Table 5). The C/N ratio of the investigated substrates ranged from 41.7 to 57.1. In particular, hay substrates exhibited a high C/N ratio (48.1-57.1), which could negatively affect methanogenesis. Therefore, it is recommended to mix these substrates with other plants to improve carbon-to-nitrogen ratio and methane yields. Additionally, the hemicellulose concentration in the switchgrass substrates ranged from 231 to 272 g/kg, while the acid detergent lignin (ADL) content varied from 41 to 57 g/kg. The lowest ADL content was found in the ensiled switchgrass substrates. The biochemical methane potential (BMP) of these substrates ranged from 302 to 331 L/kg of volatile solids (VS), with the highest BMP observed in the ensiled substrates from the non-pigmented genotype of *Panicum virgatum*.

There are different results reported in research studies conducted by other authors. Massé et al. (2010) reported specific methane yields from switchgrass silage ranging from 191 to 309 L/kg VS when prepared in mid-summer, while methane yields for substrates prepared in early autumn ranged from 191 to 250 L/kg VS. Ahn et al. (2010) investigated the impact of co-fermenting switchgrass silage with different types of manure. They found that the methane yield was 373 L/kg for the mixture of switchgrass silage and swine manure, 28 L/kg for switchgrass silage mixed with dairy manure, and only 2 L/kg for the mixture with poultry manure. Massé et al. (2011) mentioned that average specific methane yield from reed canarygrass-seeded plots was 187 L/kg VS, while from switchgrass-seeded plots 212 L/kg VS. Frigon et al. (2012) reported that methane production from fresh switchgrass harvested in the summer, after undergoing mulching, alkalization and autoclaving, reached 256.6 L/kg VS. Additionally, combining alkali pre-

treatment with manganese peroxidase further increased methane production to 297.7 L/kg VS. Grigatti et al. (2012) mentioned that switchgrass substrate was characterized by 957 g/kg organic dry matter, 429.4 g/kg carbon, 3.64 g/kg nitrogen, C/N=119 and cumulative methane yield achieved 246 L/kg VS; maize substrate - 950 g/kg organic dry matter, 416.8 g/kg carbon, 12.50 g/kg nitrogen, C/N=25 and 192 L/kg VS, while sorghum substrates - 929-949 g/kg organic dry matter, 426.9-427.4 g/kg carbon, 7.91-8.98 g/kg nitrogen, C/N=49-54 and 193-230 L/kg VS. Raposo et al. (2012) remarked that the specific methane yields of substrates from *Panicum virgatum* biomass varied from 191 to 309 l/kg VS. Butkutė et al. (2013). El-Mashad (2013) found that methane yields from switchgrass substrates after 40 days of digestion at 35°C were 127 L/kg VS, whereas at 50°C, the yield increased to 198 L/kg VS. Niu et al. (2015) reported that during batch anaerobic digestion of switchgrass, biogas production reached 268.80 L/kg VS, with a methane potential of 135.31 L/kg VS. The conversion efficiencies of material and energy from switchgrass to biogas were 36.1% and 30.1%, respectively. Zheng et al. (2015) mentioned that switchgrass substrate was characterized by 381 g/kg Cel, 356 g/kg HC, 78 g/kg lignin, C/N=31.5 and methane yield was 131.1 L/kg VS. Baute et al. (2018) analyzed the biogas produced from switchgrass via anaerobic digestion and found that the methane potential of *Panicum virgatum* ranged from 160.1 to 186.5 L/kg VS, while *Miscanthus giganteus* substrates exhibited a range from 167.5 to 229.8 L/kg VS. Similarly, Barbanti et al. (2014) reported that the methane potential of switchgrass biomass was 217 L/kg VS, whereas maize substrates yielded a higher methane potential of 316 L/kg VS. Amaleviciute-Volunge et al. (2020) remarked that the specific methane yields of substrates from *Panicum virgatum* had C/N=42.1 and methane yield 70.1 L/kg fresh mass, while *Medicago sativa* C/N=13.3 and methane yield 56.6 L/kg fresh mass. Başar et al. (2020) noted that raw switchgrass substrates contained 40.13-41.95% carbon and 0.35-0.87% nitrogen, with methane

production ranging from 215.5 to 217.1 L/kg. In contrast, switchgrass substrates post-ethanol distillation showed methane production ranging from 238.7 to 400.7 L/kg. Morozova et al. (2020) reported that switchgrass substrate had 382.1 g/kg dry matter and 95.21% organic matter, with a methane yield of 256 L/kg VS. Capecchi et al. (2016) found that the biochemical methane potential of switchgrass substrates varied from 137.5 to 300.5 L/kg dry matter, depending on the selected pretreatment.

Kupryś-Caruk et al. (2023) reported that the methane yield from pure *Panicum virgatum* silages was 310 L/kg ODM, whereas inoculated silages yielded 380 L/kg ODM. Norkeviciene et al. (2025) found that switchgrass samples collected in mid-July had a C/N ratio of 46.7-47.2, with methane production ranging from 254 to 308 L/kg VS. In contrast, switchgrass samples harvested in early August had a higher C/N ratio of 62.4-67.9 and produced 171-202 L/kg VS of methane.

Table 5. The biochemical biomethane production potential of the substrates from *Panicum virgatum* genotypes

Indices	<i>Panicum virgatum</i> (purple)			<i>Panicum virgatum</i> (green)		
	green mass	silage	hay	green mass	silage	hay
Crude protein, g/kg DM	61.00	62.00	56.00	68.00	70.00	65.00
Nitrogen, g/kg DM	9.76	9.92	8.96	10.88	12.00	10.40
Ash, g/kg DM	82.00	82.00	79.00	93.00	99.00	100.00
Carbon, g/kg DM	510.00	510.00	511.67	503.89	500.56	500.00
Ratio carbon/nitrogen	52.25	51.14	57.11	46.31	41.71	48.08
Acid detergent lignin, g/kg DM	52.00	43.00	57.00	49.00	41.00	52.00
Hemicellulose, g/kg DM	259.00	234.00	272.00	231.00	241.00	253.00
Biomethane potential, L/kg VS	311.00	325.77	302.04	317.11	330.99	312.28
Biomethane potential, L/kg DM	285.04	298.73	278.06	288.62	298.22	281.05

## CONCLUSIONS

The studied *Panicum virgatum* genotypes are distinguished by their rapid development and high dry matter productivity. The green genotype (without anthocyanin pigmentation) is characterized by superior dry matter yield, optimal crude protein concentration, and a lower content of structural carbohydrates compared to the purple genotype (with anthocyanin pigmentation).

The biochemical methane potential (BMP) of *Panicum virgatum* substrates ranged from 302 to 311 L/kg VS, with the highest biomethane potential observed in substrates from the green genotype.

These genotypes could serve as alternative forage for livestock as well as feedstock for biomethane production, contributing to renewable energy sources. Furthermore, they hold potential as starting material for breeding new cultivars of *Panicum virgatum*, a versatile crop with multiple applications.

The *Panicum virgatum* green genotype may also be a valuable source of germplasm for the development of new cultivars.

## ACKNOWLEDGEMENTS

This study has been supported by the subprogram no. 01.01.02 "Identification of valuable forms of plant resources with multiple uses for the circular economy".

## REFERENCES

- Ahn, H.K., Smith, M.C., Kondrad, S.L., White, J.W., 2010. Evaluation of biogas production potential by dry anaerobic digestion of switchgrass - animal manure mixtures. Applied Biochemistry and Biotechnology, 160: 965-975.
- Amaleviciute-Volunge, K., Slepeliene, A., Butkute, B., 2020. Methane yield of perennial grasses as affected by the chemical composition of their biomass. Zemdirbyste-Agriculture, 107(3): 243-248.
- Ashworth, A., Moore, P., King, R., Pote, D., Douglas, J.L., Jacobs, A.A., 2020. Switchgrass nitrogen

- fertility response and nutrient cycling in a hay system. *Agronomy Journal*, 112: 1963-1971.
- Badger, C.M., Bogue, M.J., Stewart, J., 1979. *Biogas production from crops and organic wastes*. *New Zealand Journal of Science*, 22: 11-20.
- Barbanti, L., Di Girolamo, G., Grigatti, M., Bertin, L., Ciavatta, C., 2014. *Anaerobic digestion of annual and multi-annual biomass crops*. *Industrial Crops and Products*, 56: 137-144.
- Başar, İ.A., Ünşar, E.K., Ünyay, H., Perendeci, N.A., 2020. *Ethanol, methane, or both? Enzyme dose impact on ethanol and methane production from untreated energy crop switchgrass varieties*. *Renewable Energy*, 149: 287-297.
- Baute, K., Van Eerd, L.L., Robinson, D.E., Sikkema, P.H., Mushtaq, M., Gilroyed, B.H., 2018. *Comparing the biomass yield and biogas potential of Phragmites australis with Miscanthus x giganteus and Panicum virgatum grown in Canada*. *Energies*, 11(9): 2198. <https://doi.org/10.3390/en11092198>
- Belanger, G., Savoie, P., Parent, G., Claessens, A., Bertran, A., Tremblay, G.F., Masse, D., Gilbert, Y., Babineau, D., 2012. *Switchgrass silage for methane production as affected by date of harvest*. *Canadian Journal of Plant Science*, 92: 1187-1197.
- Burns, J.C., Fisher, D.S., Leonard, E.S., 2014. *Warm-season perennial forages conserved as hay: nutritive value and quality*. *Technical Bulletin*, 335, 112 p.
- Butkutė, B., Lemežienė, N., Cesevičienė, J., Liatukas, Ž., Dabkevičienė, G., 2013. *Carbohydrate and lignin partitioning in switchgrass (Panicum virgatum L.) biomass as a bioenergy feedstock*. *Zemdirbyste-Agriculture*, 100 (3): 251-260.
- Capecchi, L., Galbe, M., Wallberg, O., Mattarelli, P., Barbanti, L., 2016. *Combined ethanol and methane production from switchgrass (Panicum virgatum L.) impregnated with lime prior to steam explosion*. *Biomass & Bioenergy*, 90: 22-31.
- Casler, M.D., 2012. *Switchgrass breeding, genetics, and genomics*. *Green Energy and Technology*, 94: 29-53.
- El-Mashad, H.M., 2013. *Kinetics of methane production from the codigestion of switchgrass and Spirulina platensis algae*. *Bioresource Technology*, 132: 305-312.
- Dandikas, V., Heuwinkel, H., Lichti, F., Drewes, J.E., Koch, K., 2015. *Correlation between biogas yield and chemical composition of grassland plant species*. *Energy Fuels*, 29 (11): 7221-7229.
- Davis, D., Aiken, G., Llewellyn, D.A., Lea, K., Smith, S.R., 2018. *Case study: intake and apparent digestibility by beef calves of Alamo and Cave-in-Rock switchgrass cultivars harvested as hay at 3 different maturities*. *The Professional Animal Scientist*, 34(5): 469-473.
- Dien, B.S., Jung, H.G., Vogel, K.P., Casler, M.D., Lamb, J.F.S., Iten, L., Mitchell, R.C., Sarath, G., 2006. *Chemical composition and response to dilute-acid pretreatment and enzymatic saccharification of alfalfa, reed canarygrass, and switchgrass*. *Biomass and Bioenergy*, 30: 880-891.
- Eliş, S., and Özyazıcı, M.A., 2019. *Determination of the silage quality characteristics of different switchgrass (Panicum virgatum L.) cultivars*. *Applied Ecology and Environmental Research*, 17(6): 15755-15773.
- Ferri, C., Stritzler, N., Petrucci, H., Cerqueira, E., 2000. *Effect of amount of Panicum virgatum hay offered on intake, apparent digestibility and short-term intake rate of rams*. *Animal Science*, 71: 341-347.
- Frigon, J.C., Mehta, P., Guiot, S.R., 2012. *Impact of mechanical, chemical and enzymatic pretreatments on the methane yield from the anaerobic digestion of switchgrass*. *Biomass and Bioenergy*, 36: 1-11.
- Gelley, C., Nave, R., Bates, G., 2016. *Forage nutritive value and herbage mass relationship of four warm-season grasses*. *Agronomy Journal*, 108: 1603-1613.
- Głowacka, A., Szostak, B., Klebaniuk, R., 2020. *Effect of biogas digestate and mineral fertilisation on the soil properties and yield and nutritional value of switchgrass forage*. *Agronomy*, 10(4): 490. <https://doi.org/10.3390/agronomy10040490>
- Griffin, J.L., and Jung, G.A., 1983. *Yield and forage quality of Panicum virgatum*. *Proceedings of the XIV International Grassland Congress*: 1699-1700.
- Griffiths, M., Wang, X., Dhakal, K., Guo, H., Seethepalli, A., Kang, Y., York, L.M., 2022. *Interactions among rooting traits for deep water and nitrogen uptake in upland and lowland ecotypes of switchgrass (Panicum virgatum L.)*. *Journal of Experimental Botany*, 73(3): 967-979.
- Grigatti, M., Barbanti, L., Di Girolamo, G., Cavani, L., Bertin, L., Ciavatta, C., 2012. *Anaerobic digestion of alternative energy crops*. *Proceedings of Fourth International Symposium on Energy from Biomass and Waste*, San Servolo, Venice, Italy: 1-9.
- Guretzky, J.A., Biermacher, J.T., Cook, B., Kering, M.K., Mosali, J., 2011. *Switchgrass for forage and bioenergy: Harvest and nitrogen rate effects on biomass yields and nutrient composition*. *Plant and Soil*, 339(1): 69-81.
- Jefferson, P.G., and McCaughey, W.P., 2012. *Switchgrass (Panicum virgatum L.) cultivar adaptation, biomass production, and cellulose concentration as affected by latitude of origin*. *International Scholarly Research Network ISRN Agronomy*, 2: 9.
- Kieffer, C., Hui, D., Matamala, R., Li, J., Tyler, D., Dzantor, E.K., 2023. *Evaluation of eastern gamagrass as dual-purpose complementary bioenergy and forage feedstock to switchgrass*. *GCB Bioenergy*, 15(6): 776-790.
- Kertikov, T., and Kertikova, D., 2016. *Study phenology and productivity of true millet (Panicum miliaceum L.) as non-traditional forage crop under the Pleven Region*. *Plant Science*, 52(4): 74-79.
- Kupryś-Caruk, M., Lisowski, A., Chomontowski, C., 2023. *The effect of silage additive on the kinetics of biogas production from lignocellulosic perennial*

- crops. *Journal of Water and Land Development*, 56: 58-66.
- Kwiatkowski, C., Haliniarz, M., Yakimovich, A., Harasim, E., Drabowicz-Żybura, M., 2017. *The yield protection function of selected herbicides in proso millet (Panicum miliaceum L.) crops*. *Romanian Agricultural Research*, 34: 386-394.
- Liu, Y., Hastings, A., Chen, S., Faaij, A., 2022. *The development of a new crop growth model SwitchFor for yield mapping of switchgrass*. *GCB Bioenergy*, 14(12): 1281-1302.
- Massé, D., Gilbert, Y., Savoie, P., Bélanger, G., Parent, G., Babineau, D., 2010. *Methane yield from switchgrass harvested at different stages of development in Eastern Canada*. *Bioresource Technology*, 101(24): 9536–9541.
- Mantino, A., Ragaglini, G., Nassi o di Nasso, N., Tozzini, C., Taccini, F., Bonari, E., 2015. *Alfalfa (Medicago sativa L.) overseeding on mature switchgrass (Panicum virgatum L.) stand: biomass yield and nutritive value after the establishment year*. SIA XLIV Congress, Bologna. 10.4081/ija.2016.747
- Mantino, A., Ragaglini, G., Nassi o di Nasso, N., Cappucci, A., Mele, M., Bonari, E., 2017. *Suitability of switchgrass (Panicum virgatum L.) as a forage crop in the Mediterranean area*. *Grassland Science in Europe*, 22: 194-197.
- Massé, D., Gilbert, Y., Savoie, P., Bélanger, G., Parent, G., Babineau, D., 2011. *Methane yield from switchgrass and reed canarygrass grown in Eastern Canada*. *Bioresource Technology*, 102: 10286-10292.
- Milenkovic, J., Stanisavljevic, R., Marković, J., Petrovic, M., Vasic, T., Anđelkovic, S., Terzic, D., 2018. *Biomass quality of different genotypes of switchgrass (Panicum virgatum L.) for animal feed*. *Journal on Processing and Energy in Agriculture*, 22(3): 22-124.
- Morozova, I., Oechsner, H., Roik, M., Hulsemann, B., Lemmer, A., 2020. *Assessment of areal methane yields from energy crops in Ukraine, best practices*. *Applied Sciences*, 10(13): 4431. <https://doi.org/10.3390/app10134431>
- Niu, H., Kong, X., Li, L., Sun, Y., Yuan, Z., Zhou, X., 2015. *Analysis of biogas produced from switchgrass by anaerobic digestion*. *BioResources*, 10(4): 7178-7187.
- Norkeviciene, E., Venslauskas, K., Navickas, K., Greco, C., Amaleviciute-Volunge, K., Kemesyte, V., Liatukiene, A., Petrauskas, G., Butkute, B., 2025. *Evaluating switchgrass (Panicum virgatum L.) as a feedstock for methane production in Northern Europe*. *Agriculture*, 15: 1244. <https://doi.org/10.3390/agriculture15121244>
- Petcu, V., Ioniță, M., Zaharia, T.A., Todirică, I.C., Paraschivescu, M.T., Simion, P.S., 2024. *Populațiile locale de mei (Panicum miliaceum L.) - o opțiune pentru îmbunătățirea rezilienței și biodiversității agroecosistemelor [Local populations of millet (Panicum miliaceum L.) - an option for improving the resilience and biodiversity of agroecosystems]*. *Analele INCDA Fundulea*, 92: 23-28.
- Pilat, J., Majtkowski, W., Majtkowska, G., Żurek, G., Mikołajczak, J., 2007. *The feeding value assessment of forage from some C-4 grass species in different phases of vegetation. Part 3. Panicum virgatum L.* *Plant Breeding and Seed Science*, 55: 65-73.
- Pricop, M., 2003. *Genetic control of the number of nodes per stem in millet (Panicum miliaceum L.)*. *Romanian Agricultural Research*, 19-20: 1-6.
- Rakhmetov, D.B., Vergun, O.M., Rakhmetova, S.O., 2014. *Panicum virgatum L. - promising introduced crop in M.M. Gryshko National Botanical Garden of the NAS of Ukraine*. *Plant Introduction*, 63(3): 3-14. [In Ukrainian]
- Rakhmetova, S.O., Vergun, O.M., Kulyk, M.I., Blume, R.Y., Bondarchuk, O.P., Blume, Y.B., Rakhmetov, D.B., 2014. *Efficiency of switchgrass (Panicum virgatum L.) cultivation in the ukrainian forest-steppe zone and development of its new lines*. *The Open Agriculture Journal*, 14(1): 273-289.
- Rakhmetova, S.O., Vergun, O.M., Kulyk, I.M., Blume, R.Y., Bondarchuk, O.P., Blume, Y.B., Rakhmetov, D.B., 2020. *Efficiency of switchgrass (Panicum virgatum L.) cultivation in the Ukrainian Forest-Steppe Zone and development of its new lines*. *The Open Agriculture Journal*, 14: 273-289.
- Raposo, F., De La Rubia, M.A., Fernández-Cegrí, V., Borja, R., 2012. *Anaerobic digestion of solid organic substrates in batch mode: An overview relating to methane yields and experimental procedures*. *Renewable & Sustainable Energy Reviews*, 16: 861-877.
- Razar, R.M., Qi, P., Devos, K.M., Missaoui, A.M., 2022. *Genotyping-by-sequencing and QTL mapping of biomass yield in two switchgrass F1 populations (Lowland x Coastal and Coastal x Upland)*. *Frontiers in Plant Science*, 13, 739133. 10.3389/fpls.2022.739133
- Richner, J.M., Kallenbach, R.L., Roberts, C.A., 2014. *Dual use switchgrass: Managing switchgrass for biomass production and summer forage*. *Agronomy Journal*, 106(4): 1438-1444.
- Seepaul, R., Macoon, B., Reddy, K., Evans, W., 2016. *First harvest timing and nitrogen application rate effects on chemical composition and ethanol yield of switchgrass*. *Crop, Forage and Turfgrass Management*, 2: 1-16.
- Tang, C.-C., Han, L.-P., Xie, G.-H., 2020. *Response of switchgrass grown for forage and bioethanol to nitrogen, phosphorus, and potassium on semiarid marginal land*. *Agronomy*, 10(8): 1147. <https://doi.org/10.3390/agronomy10081147>
- Tóth, S., Soltysová, B., Dupl'ák, S., Porvaz, P., 2023. *Impact of soil-applied humic ameliorative amendment on the ligno-cellulose quality and calorific value of switchgrass Panicum virgatum L.* *Agronomy*, 13: 1854. <https://doi.org/10.3390/agronomy13071854>

Țiței, V., 2025. *The quality indices of fodders from some common millet cultivars (Panicum miliaceum) under the conditions of the Republic of Moldova*. Romanian Agricultural Research, 42: 195-204.

<https://doi.org/10.59665/rar4217>

Vergun, O.M., Rakhmetov, D.B., Rakhmetova, S.O., Fishchenko, V.V., 2018. *The content of nutrients*

*and energetic value of the plant raw material of switchgrass (Panicum virgatum L.) genotypes*. Plant Introduction, 4: 82-88.

Zheng, Z., Liu, J., Yuan, X., Wang, X., Zhu, W., Yang, F., Cui, Z., 2015. *Effect of dairy manure to switchgrass co-digestion ratio on methane production and the bacterial community in batch anaerobic digestion*. Applied Energy, 151: 249-257.