

THE ENERGY POTENTIAL OF CROP RESIDUE BIOMASS

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Abstract

Crop residues represent an abundant and underutilized source of renewable energy, offering a sustainable alternative to fossil fuels. This study assessed the physicochemical properties and bioenergy potential of post-harvest residues from *Helianthus annuus*, *Zea mays*, *Sorghum* sp., *Fagopyrum esculentum*, *Silybum marianum* and *Rumex patientia* × *Rumex tianschanicus*, to evaluate their suitability for biogas/biomethane, bioethanol, and solid biofuel production. The residues contained 32-89 g/kg crude protein, 69-112 g/kg acid detergent lignin, 348-507 g/kg cellulose, and 208-292 g/kg hemicellulose. Biochemical biomethane potential ranged from 213 to 287 L/kg of dry organic matter, while theoretical ethanol yields reached 404-562 L/t. Net calorific values were 15.33-16.97 MJ/kg, demonstrating substantial energy content. These results highlight the versatility of crop residues as a renewable energy feedstock and support their strategic utilization for sustainable bioenergy production in the Republic of Moldova.

Key words: biochemical composition, biochemical methane potential, crop residues, quality indices, solid biofuel, theoretical ethanol yield.

INTRODUCTION

Agriculture is a cornerstone of the economy of the Republic of Moldova, providing food and raw materials for multiple industries. According to the National Bureau of Statistics, nearly half of the country's revenue derives from the export of agricultural and food products, with cereals and oilseeds accounting for approximately 40% of total exports.

Maize (*Zea mays*, *Poaceae*) has long been a traditional crop in Moldova. However, the total area planted with maize declined from 464,000 hectares in 2024 to approximately 300,000 hectares in 2025, largely due to adverse climatic conditions, including drought and heat waves, and rising costs of fertilizers and phytosanitary products. In response, sorghum (*Sorghum bicolor*, *Poaceae*) has gained renewed attention as a drought-tolerant alternative capable of thriving on saline-affected soils.

Sunflower (*Helianthus annuus*, *Asteraceae*) has become a leading technical crop in the Republic of Moldova, with cultivated areas reaching 414,000-418,500 hectares in 2024-2025 and annual production exceeding 800,000 tons. In addition to its economic value, sunflower is an important honey plant (Ion et al., 2018).

Similarly, milk thistle (*Silybum marianum*, *Asteraceae*) offers high-value applications in agriculture and pharmaceuticals. Its seeds, rich in silymarin, are in demand for liver-protective supplements and teas, and the plant also supports honey production with yields up to 200 kg/ha (Marceddu et al., 2022; Ion et al., 2018). Common buckwheat (*Fagopyrum esculentum*, *Polygonaceae*) has regained popularity as a nutritious, gluten-free crop with high-quality proteins, minerals, and bioactive compounds such as rutin, making it suitable for diabetic and celiac diets. It is an important honey plant. Also appreciable forage crops (Farooq et al., 2016; Heuzé et al., 2019; Țîței, 2023). *Rumex* species, including *Rumex patientia* L. and the hybrid *Rumex tianschanicus* × *Rumex patientia* (syn. *Rumex kioviensis*, *Polygonaceae*), are cultivated in Moldova, Ukraine, and Europe, China for greens, fodder, and high-biomass applications. These robust perennials exhibit rapid growth, early vegetation, and regrowth after seed and stem harvest, making them valuable for both food and bioenergy production (Țîței & Teleuță, 2015; Rolínek, 2018; Rakhmetov et al., 2024). Crop residues represent an abundant and underutilized source of feedstock for circular

economy and production energy, offering a sustainable alternative to fossil fuels.

Currently, crop residues from maize, sorghum, buckwheat, and sunflower are partially used for animal bedding and feed. Given the stagnation of the livestock sector, a significant proportion of these residues could be diverted toward renewable energy applications, providing a sustainable and secure source of biofuels, as renewable energy.

The main objective of this research was to evaluate the quality indices of crop residues remaining after seed harvesting from *Heliathus annuus*, *Zea mays*, *Sorghum* sp., *Fagopyrum esculentum*, *Silybum marianum*, *Rumex patientia* × *Rumex tianschanicus* as feedstock for the production of biogas/biomethane, bioethanol, and solid biofuels as renewable energy.

MATERIALS AND METHODS

Post-harvest crop residues from *Helianthus annuus*, *Zea mays*, *Sorghum* sp., *Fagopyrum esculentum*, *Silybum marianum* and *Rumex patientia* × *Rumex tianschanicus* were collected from experimental plots at the National Botanical Garden of Chişinău (NBGI). For each species, 100 kg of biomass was sampled. The biomass was initially chopped using a mechanical chopper and subsequently ground in a beater mill equipped with a 6 mm mesh. For analytical purposes, samples were oven-dried at 85°C, further ground to a particle size below 1 mm and thoroughly homogenized.

The chemical composition was assessed through the following indices: crude protein (CP), crude fiber (CF), crude ash (CA), acid detergent fiber (ADF), neutral detergent fiber (NDF), and acid detergent lignin (ADL), measured using near-infrared spectroscopy (NIRS) on a PERTEN DA 7200 analyzer at the Research and Development Institute for Grassland, Braşov, Romania. Hemicellulose (HC) and cellulose (Cel) contents were calculated following standard procedures. The biochemical methane potential (BMP) was estimated according to Dandikas et al. (2015). The theoretical ethanol potential (TEP) was calculated based on the conversion of cellulose and hemicellulose into hexose and pentose sugars, following Goff et al. (2010).

The elemental composition (carbon (C), hydrogen (H), nitrogen (N), and sulphur (S))

was determined via dry combustion using a Vario Macro CHNS analyzer. The ash content was measured at 550°C in a muffle furnace (HT40AL) according to SM EN ISO 18122, and calorific values (higher and lower heating values) were determined using an automatic calorimeter following SM EN ISO 18125.

This comprehensive analysis allowed for the characterization of crop residues as potential feedstock for biogas/biomethane, bioethanol, and solid biofuel production.

RESULTS AND DISCUSSIONS

The estimation of crop residue availability for bioenergy production requires a comprehensive understanding of both dry matter content and biochemical composition. These parameters are of critical importance for the collection, storage and formulation of homogeneous substrates for biofuel production, as they directly influence processing efficiency, energy yield and feedstock handling characteristics.

At the time of harvest, the investigated crops exhibited relatively similar moisture contents in their stems. Specifically, the dry matter content varied across species as follows: *Fagopyrum esculentum*, 400 g/kg; *Rumex patientia* × *Rumex tianschanicus*, 794 g/kg; *Silybum marianum*, 624 g/kg; *Sorghum* sp., 485 g/kg; *Helianthus annuus*, 723 g/kg; and *Zea mays*, 684 g/kg.

The detailed biochemical composition of the studied crop residues, as summarized in Table 1, revealed wide interspecific variation. Crude protein (CP) ranged from 30 to 89 g/kg, ash from 34 to 132 g/kg, crude fiber (CF) from 408 to 560 g/kg, acid detergent fiber (ADF) from 407 to 501 g/kg, neutral detergent fiber (NDF) from 417 to 614 g/kg, acid detergent lignin (ADL) from 69 to 112 g/kg, cellulose (Cel) from 348 to 507 g/kg and hemicellulose (HC) from 208 to 292 g/kg of dry matter.

Among the species, *Fagopyrum esculentum* residues were distinguished by their relatively high crude protein content and comparatively low levels of structural cell wall components. In contrast, the crude protein concentrations in residues of *Silybum marianum* and *Sorghum* sp. were comparable to those of *Zea mays* stover and significantly higher than those observed in *Rumex patientia* × *Rumex tianschanicus* and *Helianthus annuus*, suggesting their potential as

more balanced feedstock in terms of protein availability.

Ash content was notably elevated in *Silybum marianum*, *Fagopyrum esculentum* and *Sorghum* sp. residues, likely reflecting the prolonged retention of leaves on stems prior to harvest. The distribution of fibrous components and lignin varied considerably among species. The lowest values of ADF, NDF and ADL were observed in *Fagopyrum esculentum*, followed by *Zea mays*, whereas *Silybum marianum* and *Helianthus annuus* exhibited the highest levels, indicating greater recalcitrance to biochemical conversion in these species.

Regarding polysaccharide composition, *Sorghum* straw contained higher cellulose and hemicellulose contents relative to *Zea mays*, *Rumex patientia* × *Rumex tianschanicus* and *Silybum marianum*, but remained lower than that of *Helianthus annuus* stover. This variation underscores the influence of species-specific structural traits on biomass degradability and energy yield potential.

Overall, these results highlight the substantial heterogeneity in dry matter content and biochemical composition among the examined crop residues, emphasizing the importance of species selection and substrate characterization in optimizing bioenergy production.

Table 1. The biochemical composition, biomethane and bioethanol potential of the studied crop residues

Indices	<i>Fagopyrum esculentum</i>	<i>Rumex patientia</i> × <i>Rumex tianschanicus</i>	<i>Silybum marianum</i>	<i>Sorghum</i> sp.	<i>Helianthus annuus</i>	<i>Zea mays</i>
Crude protein, g/kg DM	89	32	53	49	30	52
Crude fibre, g/kg DM	408	520	495	541	560	463
Minerals, g/kg DM	84	53	132	88	34	40
Acid detergent fibre, g/kg DM	417	517	583	583	614	499
Neutral detergent fibre, g/kg DM	625	757	861	875	877	749
Acid detergent lignin, g/kg DM	69	83	112	101	107	82
Cellulose, g/kg DM	348	434	471	482	507	417
Hemicellulose, g/kg DM	208	240	278	292	263	250
Biomethane potential, L/kg VS	287	255	215	236	213	260
Theoretical ethanol potential, L/t ODM	404	490	544	562	559	484
- from hexose sugars, L/t ODM	261	325	353	362	379	313
- from pentose sugars, L/t ODM	143	165	191	200	180	171

Several studies have characterized the biochemical composition of crop residues from the species investigated in this study, providing useful benchmarks for assessing their potential as bioenergy feedstocks. *Rumex patientia* × *Rumex tianschanicus* biomass was reported by Barbash et al. (2011) to contain 37.8% cellulose, 21.9% pentosans, 21.4% lignin and 3.5% ash.

Sunflower (*Helianthus annuus*) residues have been extensively studied. Mathias et al. (2015) further distinguished sunflower stem fractions, reporting 48% cellulose and 14% lignin in the stem bark versus 31.5% cellulose and 2.5% lignin in the stem pith. Yue et al. (2018) found sunflower stalks contained 37.8% cellulose, 17.1% hemicellulose, and 12.3% lignin. Heuze et al. (2015) reported the following indices for sunflower stover (stalks and heads) 758 g/kg dry matter, 5.7% CP, 1.5% EE, 48.1% CF, 66.9% NDF, 56.6% ADF, 15.7% lignin. Gholami-Yangije et al. (2019) reported sunflower stalks contained 2.26% crude protein (CP), 85.09% neutral detergent fiber (NDF), 72.72% acid

detergent fiber (ADF) and 15.25% acid detergent lignin (ADL). Halysh et al. (2016) found that sunflower stover had 36.2% cellulose, 25.2% hemicellulose, 14.1% lignin and 3.4% ash.

Buckwheat (*Fagopyrum esculentum*) residues were reported by Smuga-Kogut et al. (2019) to contain 42.08% cellulose, 8.38% hemicellulose, and 16.97% lignin, while Heuze et al. (2019b) noted the following indices of buckwheat residues 872g/kg dry matter, 4.6% CP, 1.2% EE, 50.4% CF, 73% NDF, 56% ADF, 10.7% lignin. Acar et al. (2015) reported similar compositions with 4.0% CP, 1.7% ether extract (EE), 49% ADF, 73% NDF, 10.7% lignin and 6.9% ash.

Maize (*Zea mays*) stover exhibits substantial variability in biochemical composition. Heuze et al. (2019a) reported the following indices for maize stover 928 g/kg dry matter, 2.9% CP, 0.9% EE, 40.7% CF, 75% NDF, 49.6% ADF, 7.4% lignin. Pattanaik (2019) reported cellulose content ranging from 31.3 to 49.4%, hemicellulose 21.1-26.2%, lignin 3.1-8.8%, CP

3.6-8.7%, lipids 0.3-1.3%, and ash 4.2–6.3%. Dell’Omo (2025) reported 487 g/kg ADF, 794 g/kg NDF, and 89 g/kg ADL in maize stover, while Khan et al. (2024) reported 41.43% cellulose, 26.10% hemicellulose, and 8.13% lignin in maize stalks. Li et al. (2014) found maize stover with 933.8 g/kg dry matter, 95.16% organic matter, 4.05% CP, 1.31% EE, 71.93% NDF, 41.36% ADF, and 6.16% ADL. Nasir and Kamaruddin (2023) determined that kernel maize stalk dry matter contained 4.09% CP, 0.47% fat, 2.22% ash, 27.23% crude fiber (CF), and 60.99% nitrogen-free extract (NFE), whereas sweet corn stalks contained 10.47% CP, 1.32% fat, 4.56% ash, 27.05% CF, and 51.42% NFE. Wattanaklang et al. (2016) reported maize stover with 5.8% CP, 27.38% CF, 1.90% EE, and 2.08% ash, and Zhou et al. (2019) observed sweet corn stover containing 72.3 g/kg CP, 18.1 g/kg EE, 134.1 g/kg water-soluble carbohydrates (WSC), 667.8 g/kg NDF, 426.3 g/kg ADF and 80.8 g/kg starch. Halysh et al. (2016) reported that maize stover had 41.2% cellulose, 20.3% hemicellulose, 20.7% lignin and 2.8% ash.

Collectively, these studies demonstrate significant interspecific and intraspecific variability in the biochemical composition of crop residues, reflecting differences in plant structure, harvest timing and tissue type. Anaerobic digestion is a microbial process in which organic compounds, including proteins, lipids, cellulose and hemicellulose, are converted by microorganisms such as methanogens and sulfate-reducing bacteria into biogas. Biogas primarily consists of methane, carbon dioxide and hydrogen sulfide, and represents an environmentally friendly and renewable energy source. In addition, the residual digestate is nutrient-rich and can be applied as an organic fertilizer, contributing to a circular, sustainable approach to resource utilization.

The biodegradability of lignocellulosic biomass in anaerobic digestion is strongly influenced by its chemical composition, particularly the structural carbohydrates and lignin content, as well as the carbon-to-nitrogen (C/N) ratio.

In the present study, the C/N ratios of the investigated crop residues ranged from 31 to 97, with the most favorable ratio observed in *Fagopyrum esculentum*, followed by *Zea mays* (Figures 1-2).

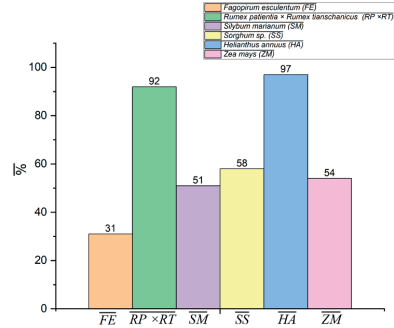


Figure 1. Carbon / Nitrogen Ratio

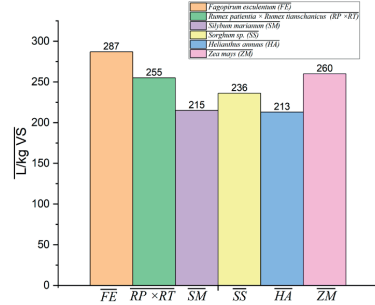


Figure 2. Biochemical Potential, L/kg VS

Differences in hemicellulose and lignin contents among substrates were also critical in determining biomethane yields. The biochemical methane potential (BMP) of the studied residues varied from 213 to 287 L/kg of organic dry matter (ODM). *Fagopyrum esculentum* residues exhibited the highest BMP, while comparable methane potentials were observed in *Zea mays* and *Rumex patientia* × *Rumex tianschanicus*, likely due to their optimal lignin content. In contrast, substrates from *Helianthus annuus*, *Silybum marianum* and *Sorghum* sp. demonstrated lower BMP values, reflecting their higher lignin and structural fiber contents, which reduce biodegradability.

Several studies have reported data on the biomethane production potential of crop residue substrates. Dell’Omo (2025) found that the methane yield and biogas composition of maize stover raw material were 199.6 m³/t VS and 52.0%, respectively, while for pretreated maize stover, the values were 219.8 m³/t VS and 51.1%. Mazurkiewicz et al. (2019) reported that the methane productivity of maize straw substrates ranged from 201 to 207 m³/t. El-Araby (2024) showed that methane production

from the anaerobic digestion of maize stover was 338 L/kg, while wheat straw yielded 290 L/kg. Amon et al. (2007) reported that the specific methane yield of substrates from two sunflower cultivars significantly decreased during the growing season, from 454 to 190 L/kg VS. Mursec et al. (2009) reported that the highest biomethane production was achieved by the sunflower substrate (283 L/kg VS), followed by the sorghum substrate (188 L/kg VS) and maize (187 L/kg VS).

Spyridonidis et al. (2019) reported that the methane yields of sunflower stalk and head residues were 112.2 and 183.0 L/kg TS, respectively, but after alkaline pretreatment, the yields increased to 150.7 and 196.4 L/kg TS. Zhurka et al. (2020) found that the highest methane production, 268.35 L/kg VS, was achieved from pretreated sunflower head residues.

Second-generation liquid biofuels, particularly cellulosic bioethanol, have attracted considerable attention from researchers, industry stakeholders, and policymakers, driven by the depletion of fossil fuel resources and the rapidly rising energy prices. Cellulosic bioethanol is widely regarded as a promising “drop-in” fuel capable of partially or fully substituting gasoline in the transportation sector. Compared with conventional gasoline, ethanol offers several notable advantages when used in internal combustion engines: it possesses a higher octane number, enhancing resistance to engine knock; it has a lower freezing point, which is beneficial in cold climates; and its combustion results in lower net CO₂ emissions, contributing to climate mitigation efforts.

The efficiency of ethanol production is influenced by multiple factors, including the type and chemical composition of the biomass, plant species and variety, growth conditions, and stage of maturity at harvest. Understanding these factors is essential for optimizing substrate selection and maximizing ethanol yield from lignocellulosic residues.

The theoretical ethanol yield of the studied crop residues is presented in Figure 3, illustrating the variability in potential ethanol production among different species.

The estimated theoretical ethanol yield from hexose and pentose sugars varied among the studied crop residues. *Fagopyrum esculentum*

residues exhibited the lowest potential, at 404 L/t, whereas *Sorghum* sp. and *Helianthus annuus* substrates reached the highest values, ranging from 559 to 562 L/t. The substrate from *Silybum marianum* displayed an intermediate yet notably high theoretical bioethanol potential of 544 L/t. In contrast, residues from *Rumex patientia* × *Rumex tianschanicus* and *Zea mays* showed considerably lower ethanol potential, with no significant differences observed between them.

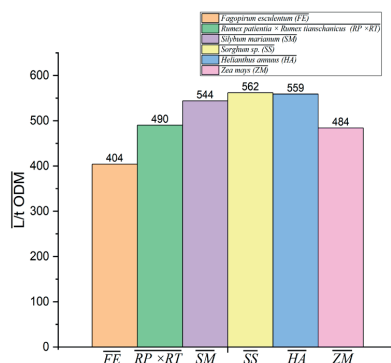


Figure 3. Theoretical Ethanol Potential, L/tonne ODM

The theoretical ethanol potential and chemical composition of various lignocellulosic crop residues have been extensively investigated in the literature, providing critical insights into their suitability as substrates for bioethanol production. Goff et al. (2010) reported that the theoretical ethanol potential of sorghum biomass ranged from 560 to 610 L/t of dry biomass. Kikas et al. (2014) reported that the chemical composition of sunflower plants was characterized by 5.18% hemicellulose, 34.06% cellulose, 7.72% lignin, 9.78% ash, a potential ethanol yield of 49 g/m², hydrolysis efficiency of 33.08%, and fermentation efficiency of 66.36%. In comparison, Jerusalem artichoke harvested in September and October contained 4.50-5.48% hemicellulose, 20.95-25.99% cellulose, 5.05-5.70% lignin, 4.56-5.15% ash, with potential ethanol yield of 38-40 g/m², hydrolysis efficiency of 74.70-77.88%, and fermentation efficiency of 38.14-44.19%.

Mathias et al. (2015) noted that sunflower stem bark contained 48% cellulose and 14% lignin, whereas the stem pith contained 31.5% cellulose and 2.5% lignin. Yue et al. (2018) reported that

sunflower stalks contained 37.8% cellulose, 17.1% hemicellulose, and 12.3% lignin.

According to Pattanaik (2019), maize stover biomass contained 31.3-49.4% cellulose, 21.1-26.2% hemicellulose, 3.1-8.8% lignin, 3.6-8.7% crude protein, 0.3-1.3% ether extract (EE), and 4.2-6.3% ash. In contrast, Jerusalem artichoke stem pith contained 67.7% alpha-cellulose, 4.6% hemicellulose, 7.6% lignin, and 1.3% ash. Gholami-Yangije et al. (2019) reported that sunflower stalks contained 2.26% crude protein, 85.09% neutral detergent fiber (NDF), 72.72% acid detergent fiber (ADF), and 15.25% acid detergent lignin (ADL).

Țiței et al. (2021) revealed that the dry stems of *Helianthus tuberosus* ‘Solar’ contained 276 g/kg cellulose, 176 g/kg hemicellulose, 98.04 g/kg hexose sugars, and 45.4 g/kg pentose sugars, with a theoretical bioethanol yield of 598 L/kg. Overall, these studies highlight the considerable variability in cellulose, hemicellulose, and lignin contents among crop residues, which directly influences their theoretical ethanol potential.

Phytomass, including woody plants and crop residues, has long served as a primary energy source for humans, particularly for heating and cooking. The valorization of energy biomass in the form of densified solid fuels, such as pellets and briquettes, is widely favored due to several advantages: it reduces biomass volume, lowers

transportation costs, facilitates handling, and increases energy density per unit of volume.

Ash content is a critical parameter in determining the quality of solid biofuels. High ash levels can reduce combustion efficiency, accelerate corrosion, promote clinker formation in combustion chambers, and cause wear and physical damage to heating systems. As previously shown in Table 1, the crop residues investigated in this study exhibited considerable variability in ash content. *Helianthus annuus* and *Zea mays* residues were found to have more favorable, lower ash concentrations, whereas very high ash levels were observed in *Silybum marianum*, *Fagopyrum esculentum* and *Sorghum* sp. residues. Consequently, the use of these high-ash residues in densified solid fuel production is recommended in combination with low-ash-content biomass, such as woody materials, to optimize fuel quality.

The utilization of crop residues for densified solid fuel production also requires careful characterization of their elemental composition. During combustion, the oxidation of carbon and hydrogen releases energy, with carbon contributing most significantly to the overall heating value, while increased hydrogen content further enhances the net calorific value. In contrast, high levels of nitrogen (N), sulfur (S) and chlorine (Cl) in biomass can lead to increased emissions of harmful compounds during combustion.

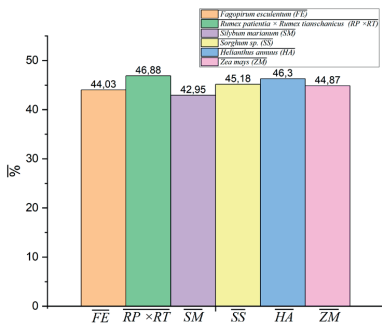


Figure 4. Carbon content, %

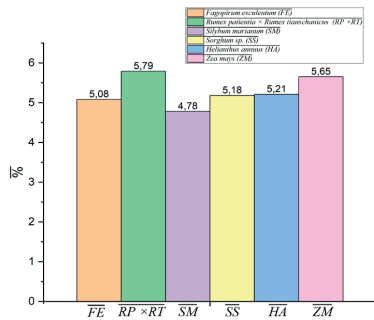


Figure 5. Hydrogen content, %

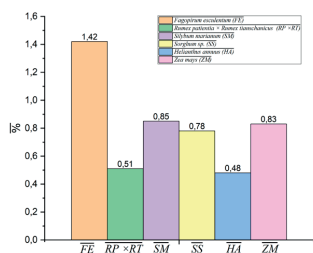


Figure 6. Nitrogen content, %

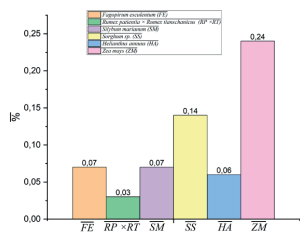


Figure 7. Sulphur content, %

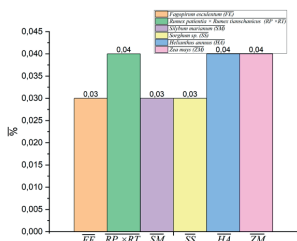


Figure 9. Chlorine content, %

Our results indicate that carbon and hydrogen concentrations vary significantly among the studied crop residues, with relatively higher levels observed in *Rumex patientia* × *Rumex tianschanicus* and *Helianthus annuus*. *Fagopyrum esculentum* residues exhibited particularly high nitrogen content, whereas *Zea mays* residues showed elevated sulphur levels.

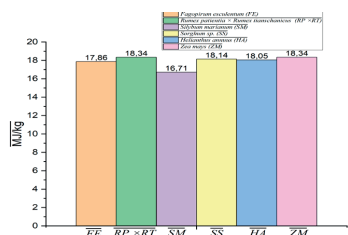


Figure 10. Gross calorific values of the studied residues, MJ/kg

The energy values of studied crop residues are presented in Figures 10-11. It was determined that the gross calorific values (GCV) of the The The elemental composition of the studied crop residues is summarized in Figures 4-11, providing essential information for assessing their suitability for solid biofuel applications residues ranged from 16.71 to 18.34 MJ/kg, while the corresponding lower calorific values (LCV) ranged from 15.33 to 16.97 MJ/kg.

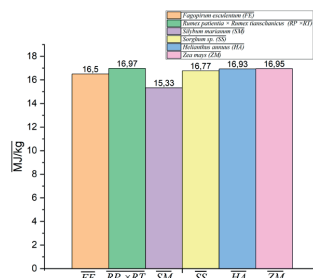


Figure 11. Lower calorific values of the studied residues, MJ/kg

Among the substrates, the net calorific value of *Rumex patientia* × *Rumex tianschanicus* residues was found to be optimal, exceeding that of *Zea mays* and *Helianthus annuus* residues and substantially higher than that of *Sorghum* and *Fagopyrum esculentum*. In contrast, *Silybum marianum* residues exhibited comparatively lower calorific values, likely due to their reduced carbon content coupled with very high ash levels.

Several studies have reported on the quality indices and energy values of crop residues. According to Unal& Alibas (2006) that sunflower stalks had 7.6 % ash and 18.647MJ/kg. Petříková (2011) found that *Rumex* dry matter contained 1.85% ash, 19.17 MJ/kg HHV, 17.89 MJ/kg LHV, 5.5% moisture, 48.62% carbon (C), 0.05% sulphur (S), 0.49% nitrogen (N), and 42.88% oxygen (O). Sulas et al. (2008) reported that the calorific value of whole dry biomass from *Silybum marianum* phytomass was 14.8 GJ/t. Sánchez et al. (2009) found that sunflower biomass contained 8.1% moisture, 74.5% volatile matter, 8.3% ash, 19.8% fixed carbon, 41.21% C, 5.14% H, 49.82% O, 2.54% N and 15.7 MJ/kg calorific value.

Hăbășescu (2011) reported that pellets produced from sunflower stems had 3.78% ash and 14.8 MJ/kg LHV; maize stem pellets contained 5.14% ash and 14.2 MJ/kg LHV; and wheat straw pellets had 6.25% ash and 14.3 MJ/kg LHV. Ledda et al. (2013) analysed milk thistle biomass and found 79.3-87.5% volatile matter, 9.6-16.7% ash, 7.5-10.9% fixed carbon, 37.0-42.9% C, 5.3-5.9% H, 49.8-50.0% O, 0.5-1.2% N, 0.3% S and a calorific value of 16.1-18.1 MJ/kg.

Marian et al. (2013) reported that maize stover contained 4.15-5.32% ash, 17.71-18.16 MJ/kg HHV, and 16.51-16.95 MJ/kg LHV, whereas corn cobs contained 1.25% ash, 14.20 MJ/kg HHV, and 13.62 MJ/kg LHV. Huang (2014) noted that briquettes from sunflower stems had a calorific value of 4,300 kcal/kg (18.0 MJ/kg) and 4.3% ash, wheat straw briquettes had 4,100 kcal/kg (17.1 MJ/kg) and 8.0% ash, compared with wood chips, which contained 4,785 kcal/kg (20.0 MJ/kg) and 1.2% ash.

Heuze et al. (2015) reported that sunflower stover 8.4% ash and 18.6 MJ/kg gross energy; maize stover 7.1 % ash and 18.2 MJ/kg gross energy; buckwheat residues respectively 7.2% ash and 18.7 MJ/kg gross energy. Mathias et al. (2015) found that sunflower stem bark had a heat capacity of 14 MJ/kg, while stem pith had 13 MJ/kg. Muntean et al. (2018) reported that maize stover contained 4.40% ash and 17.8 MJ/kg HHV, while biomass from alnum sorghum contained 3.71% ash and 18.6 MJ/kg HHV. Yue et al. (2018) noted that sunflower biomass contained 79 g/kg ash, 440 g/kg C, 58 g/kg H, 422 g/kg O, 9 g/kg N, and 16.7 MJ/kg LHV. Alatzas et al. (2019) reported that corn agricultural waste had 4.5% ash and 14 MJ/kg LHV. Heuze et al. (2019) found that *Fagopyrum esculentum* straw had an HHV of 18.7 MJ/kg. Rolinec (2018) observed that gross energy values varied from 18 to 19.04 MJ/kg. Kraszkiewicz et al. (2019) determined that buckwheat straw contained 14.49% moisture, 6.28% ash, 44.4% C, 5.56% H, 0.88% N, 0.13% S, 0.12% Cl, and 15.72 MJ/kg combustion heat. Bilyk et al. (2020) reported that pellets from *Fagopyrum esculentum* contained 8.9% moisture, 7.3% ash, 591 kg/m³ bulk density, 1,223 kg/m³ specific density, and 95.3% durability, whereas pellets from *Fagopyrum tataricum* had 9.2% moisture, 6.2% ash, 639

kg/m³ bulk density, 1,237 kg/m³ specific density, and 96.1% durability.

CONCLUSIONS

The investigated crop residues exhibited considerable variability in their biochemical composition, reflecting their suitability for different bioenergy applications. Crude protein ranged from 32 to 89 g/kg, acid detergent lignin from 69 to 112 g/kg, cellulose from 348 to 507 g/kg and hemicellulose from 208 to 292 g/kg, which are key determinants of their conversion potential.

The biochemical methane potential ranged from 213 to 287 L/kg dry organic matter, while the theoretical ethanol potential varied between 404 and 562 L/t organic matter. Net calorific values of the residues were 15.33–16.97 MJ/kg, confirming their suitability as feedstocks for biofuel production.

Specific crop residues show preferential applications: *Fagopyrum esculentum* is particularly promising for biogas production due to its favorable composition. *Silybum marianum*, *Sorghum* sp. and *Helianthus annuus* are well suited for cellulosic bioethanol production. *Rumex patientia* × *Rumex tianschanicus*, *Zea mays*, and *Helianthus annuus* are ideal for the production of densified solid fuels.

These results highlight the versatile utility of crop residues as renewable energy feedstocks and provide guidance for their targeted application in biogas, bioethanol and solid fuel production systems.

ACKNOWLEDGEMENTS

This study has been supported by the subprograms no. 01.01.02 and no. 02.04.07, funded by the Ministry of Education and Research, Republic of Moldova.

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