THE QUALITY INDICES OF ENERGY BIOMASS FROM SOME *BRASSICACEAE* SPECIES IN MOLDOVA

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Abstract

The Brassicaceae family includes many economically important species used as edible crops, industrial oilseeds, spices, fodder, and vegetables. This study was aimed to determine the quality indices of energy biomass from four Brassicaceae species - *Brassica napus*, *Bunias orientalis*, *Isatis tinctoria*, and *Sinapis alba* - grown in the experimental plots of the "Alexandru Ciubotaru" National Botanical Garden (Institute) of Moldova State University, Chișinău. The lignocellulosic composition of the harvested biomass showed that the dry matter contained 401-424 g/kg of cellulose, 191-226 g/kg of hemicellulose, and 83-88 g/kg of acid detergent lignin. The theoretical ethanol yield from cell wall carbohydrates was estimated to range from 430 to 473 L/t. The biochemical methane potential of the substrates varied from 232 to 268 L/kg of organic dry matter, indicating their suitability as co-substrates in biogas production systems.

The physical and mechanical properties of the biomass included: ash content of 5.48-6.40%, 18.34-18.60 MJ/kg higher heating value, and 17.00-17.40 MJ/kg lower heating value. These characteristics suggest that the studied species can also serve as suitable feedstock for the production of solid densified fuels such as pellets.

Keywords: biochemical methane potential, *Brassica napus*, *Bunias orientalis*, energy biomass, *Isatis tinctoria*, pellets, *Sinapsis alba*, theoretical ethanol yield

The global demand for energy continues to rise in order to meet increasing consumption. Environmental concerns and the depletion of fossil fuel reserves have prompted both the scientific and industrial communities to focus on the development of alternative, renewable energy sources. Among these, biomass is considered one of the most promising renewable energy sources, with significant potential to meet the energy needs of both developed and developing countries. Its use contributes to reducing greenhouse gas emissions and addressing the broader challenges of climate change. Although the concept of generating energy from biomass is not new – humans have burned plant biomass, such as wood, for cooking and heating for thousands of years – modern technologies now allow for more efficient and sustainable energy conversion. Lignocellulosic biomass residues, derived from agricultural crops and livestock manure, offer several advantages, including sustainability, availability and low greenhouse gas emissions. The conversion of agro-industrial waste into bioenergy or biofuels has gained growing attention in recent years, particularly because it does not compete with food production and supports the transition toward a circular bioeconomy. As a result, this area of research continues to attract significant interest from scientists worldwide (Alluvione F. *et al*. 2011; Habashescu I., Cerempei V., 2012; Marian G., 2014; Gudîma A., 2017; Pavlenco A. *et al*. 2018; Doroftei V. *et al*. 2021; Rozenfelde, L. . *et al*. 2021; Casau M. *et al*. 2022- Marian G. *et al*. 2022; Akter, M.M. *et al*., 2024; El-Araby R. 2024; Naveed M. *et al*. 2024; Ye Y. *et al*. 2024; Abbasi-Riyakhuni M. et al. 2025; Guo T.X., and Liang K.W., 2025; Liang K.W., and Yan S.D., 2025).

Brassicaceae is one of the most important plant families, comprising 338 genera and 3,709 species distributed worldwide. In the spontaneous flora of Bessarabia, the Brassicaceae family is represented by 49 genera and 97 species. This family includes numerous economically important species, cultivated for edible use, industrial oilseeds, condiments, fodder, and as vegetables. Among these, canola or oilseed rape (*Brassica napus*) is the most important oil crop within the Brassicaceae family. Additionally, *Brassica oleracea* and *Raphanus sativus* are significant vegetable crops. The family also includes species with potential in biodiesel and protein production, such as: *Camelina sativa, Eruca vesicaria, Crambe abyssinica* and *Brassica carinata*, while *Isatis tinctoria* is historically known as a source of the blue dye indigo. In the "Alexandru Ciubotaru" National Botanical Garden (Institute) of Moldova

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State University, various *Brassicaceae* species have been studied over the past decades for their potential as fodder plants, melliferous resources and energy crops (Teleuta A.S., 1989a, 1989b; Teleuta A.S. & Cretu L.G., 1989; Ţîţei V., 2016, 2021, 2022a, 2022b; Ţîţei V. & Roşca I., 2021; Cozari S. et al., 2022; Cîrlig N. et al., 2023, 2024).

Additionally, the study explores the potential valorization of this biomass as a feedstock for solid, liquid and gaseous biofuels.

The main goal of this study was to determine the quality indices of energy biomass from four Brassicaceae species - *Brassica napus*, *Bunias orientalis*, *Isatis tinctoria* and *Sinapis alba*, to obtain various types of biofuels as sources of clean and renewable energy.

MATERIALS AND METHODS

The Brassicaceae species *Brassica napus*, *Bunias orientalis*, *Isatis tinctoria* and *Sinapis alba*, cultivated in the experimental plots of the "Alexandru Ciubotaru" National Botanical Garden (Institute) of Moldova State University, Chișinău, were selected as the subjects of this research.

Figure 1. **Barssicaceae species in the collection of "Alexandru Ciubotaru" National Botanical Garden (Institute) of Moldova State University**

After seed harvesting, the residual biomass was chopped using a stationary forage unit, then milled in a beater mill with a 6 mm mesh sieve. For analysis, samples were oven-dried at 85°C, ground to <1 mm, and homogenized. Elemental composition, specifically, the total carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) content, was determined by dry combustion using a Vario Macro CHNS analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). Biomass densification was carried out using pelleting equipment. The ash content and energy value of both the dry biomass and the resulting pellets were measured according to standardized protocols at the Technical University of Moldova.

To analyze the cell wall composition of the biomass, the contents of neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) were determined using Near-Infrared Spectroscopy (NIRS) with a PERTEN DA 7200 analyzer at the Research-Development Institute for Grassland, Brașov, Romania. The cellulose content was calculated as ADF minus ADL, and hemicellulose – as NDF minus ADF. The Theoretical Ethanol Potential (TEP) was calculated based on the equations proposed by Goff et al. (2010), considering the conversion of cellulose and hemicellulose into hexose (H) and pentose (P) sugars. The biochemical methane potential (BMP) was estimated following the method described by Dandikas V. *et al.* (2015).

RESULTS AND DISCUSSIONS

Biomass can be converted into solid, liquid or gaseous fuels through various physical, chemical and biological conversion processes. Defining clear evaluation criteria to assess biomass quality has become increasingly important, both regionally and globally, to identify the most suitable processing technologies and optimize the type of biofuel produced, thereby enhancing the efficiency of biomass utilization for renewable energy generation.

The quality indices of the studied Brassicaceae biomass, including elemental composition, ash content and calorific value, are presented in Table 1. The dry matter of the analyzed biomass samples contained: 44.31-45.64% carbon, 4.99-5.17% hydrogen, 0.62-1.58% nitrogen, 0.07-0.23% sulphur, 5.48-6.40% ash, 18.34-18.60 MJ/kg GCV and 17.00-17.40 MJ/kg NCV.

Table 1.

The elemental composition, ash content and the energy value of biomass and pellets from the studied *Brassicaceae* species

Indices	*Brassica napus*	*Bunias orientalis*	*Isatis tinctoria*	*Sinapis alba*
Elemental composition				
Carbon, % DM	45.60	45.24	44.36	45.64
Nitrogen, % DM	0.92	1.22	0.61	1.58
Hydrogen, % DM	5.14	5.17	4.99	5.12
Sulphur, % DM	0.07	0.19	0.13	0.23
Oxygen, % DM	48.30	48.18	49.91	47.43
Ash content of biomass, % DM	5.85	6.40	6.04	5.48

Gross calorific value of biomass, MJ/kg DM	18.60	18.45	18.34	18.57
Net calorific value of biomass, MJ/kg DM	17.40	17.08	17.00	17.20
Net calorific value of pellets, MJ/kg DM	15.70	15.04	15.01	15.23

Among the species analyzed, *Isatis tinctoria* had the lowest carbon and hydrogen content, which negatively affected its calorific value compared to the other Brassicaceae species. It is worth noting that the biomass residues of all studied Brassicaceae species showed relatively high levels of nitrogen, sulphur and ash. Particularly high concentrations of nitrogen and sulphur were found in the biomass of *Bunias orientalis* and *Sinapis alba*, which may contribute to increased emissions of toxic gases during combustion. Additionally, the elevated ash content observed in *Bunias orientalis* biomass may promote slag formation on heating equipment surfaces. The pellets produced from these biomass sources, with a moisture content of approximately 10%, exhibited a net calorific value of 15.01-15.70 MJ/kg. Among them, pellets derived from *Brassica napus* and *Sinapis alba* demonstrated higher energy content, making them more suitable for bioenergy applications.

Several authors have reported varying results regarding the quality indices of biomass and solid biofuels derived from Brassicaceae species. Karaosmanoğlu F. *et al.* (1999) reported that rapeseed straw and stalks contained 12.64% moisture, 5.87% ash, 75.55% volatile matter, 18.58% fixed carbon, and had a bulk density of 141.17 kg/m³. Heneman P. & Červinka J. (2007) observed a gross calorific value of 18.50 MJ/kg for *Isatis tinctoria* biomass and 17.48 MJ/kg for *Brassica napus* straw. Zabaniotou A. *et al.* (2008) reported that rapeseed residues had 3.95% ash, 71.01% volatile matter, 23.04% fixed carbon, a gross calorific value of 16.8MJ/kg, and a net calorific value of 16.37 MJ/kg. Chico-Santamarta L. *et al.* (2009) noted an average gross calorific value of 17.4 MJ/kg in canola straw, while in a later study, Chico-Santamarta *et al.* (2012) reported rapeseed stalk pellets had 6.74-9.75% ash and gross calorific value values of 16.91-17.89 MJ/kg.

Greenhalf C.E. *et al.* (2012) found rapeseed straw to contain 6.58% ash, 76.9% volatile matter, 11.88% fixed carbon, and a gross calorific value of 18.94 MJ/kg, while wheat straw, by comparison, had 4.89% ash, 79.92% volatile matter, 15.18% fixed carbon and a gross calorific value of 18.69 MJ/kg. Habashescu I.and Cerempei V. (2012) reported that rapeseed straw had 6.20% ash and 16-17 MJ/kg calorific value. Fuksa P. *et al.* (2013) reported a gross calorific value of 17.29-18.72 MJ/kg for *Brassica napus* biomass and 17.03-18.46 MJ/kg for *Sinapis alba*. Maroušek J. (2013) found that rapeseed straw pellets had a gross calorific value of 15.4 MJ/kg and a specific density of 944 kg/m³. According to Plíštil D. et al. (2014), crambe briquettes had a BD of 670-800 kg/m³, destruction force of 25-55 N/mm, and compaction pressure of 14-21 MPa; while rapeseed straw briquettes had 800–860 kg/m³ BD, 24-40 N/mm destruction force and 35-40 MPa compaction pressure.

I. Niedziółka et al. (2015) reported that pellets made from rape straw were characterized by 12.3% moisture content, a calorific value of 17.3 MJ/kg, and 82.4% mechanical durability. Gao Y. et al. (2017) noted that rapeseed stalk contained 47.47% C, 5.96% H, 41.09% O, 0.47% nitrogen, and 0.22% S. Stasiak M. *et al.* (2017) found that rapeseed straw pellets had 7.92% ash, a lower calorific value of 14.3-16.5 MJ/kg, and 40.6-54.8% mechanical durability. Cástková T. *et al.* (2018) reported that unmodified rape straw contained 95.52% volatile solids, 1,340 mg/kg sulphur, and a calorific value of 17.79 MJ/kg, while modified rape straw had 94.60–96.97% volatile solids, 323-436 mg/kg sulphur and a calorific value of 17.6-18.4 MJ/kg. Gageanu I. *et al.* (2018) found that pellets made from rapeseed stalk had 10.54% moisture content and an energy value of 3780.21 kcal/kg.

Maj G. *et al.* (2019) determined that the heat of combustion of white mustard biomass was 15.55 MJ/kg. Stolarski M.J. *et al.* (2019) found that rapeseed straw contained 27.98% moisture content, 18.93 MJ/kg gross calorific value, 12.95 MJ/kg net calorific value, 20.69% fixed carbon, 73.84 volatile matter, 5.47% ash, 46.89% carbon, 5.46% hydrogen, 1.26% nitrogen, 0.315% sulphur, 0.418% chlorine. Kachel M. *et al.* (2020) stated that rapeseed straw pellets had 89.08 % durability, 18.45 MJ/kg gross calorific value, 17.27 MJ/kg net calorific value, 9.59% ash, 47.42% carbon, 5.38 % hydrogen, 1.15% nitrogen, 0.78 % sulphur, 0.84% chlorine. Vergun O. *et al.* (2021) reported that in *Bunias orientalis* plants ash content ranged from 6.79 to 9.2% and the energy value of the phytomass ranged from 3337 to 3498 cal/g. Stolarski M.J. *et al.* (2024) determined that rapeseed straw had 15.85-25.09% moisture content, 17.97-19.95 % fixed carbon, 72.48-74.69% volatile matter, 5.95-7.56% ash, 43.41-45.70% carbon, 5.12-5.61% hydrogen, 0.97-1.18%% nitrogen, 0.193-0.394% sulphur, 0.233-0.425% 17.97-18.42 MJ/kg gross calorific value, 12.14-14.35 MJ/kg net calorific value. Jankowski

K. J. (2025) reported that lower heating value of white mustard straw varied from 15.42 to15.99 MJ/kg. According to Stolarski M.J. *et al.* (2025) the rapeseed biomass pellets is characterized by 8.19 % moisture content, 19.65 % fixed carbon, 75.3%5 volatile matter, 607.85 kg/m^3 bulk density, 18.91 MJ/kg gross calorific value, 16.03 MJ/kg net calorific value, 5.95-7.56% ash, 48.38% carbon, 6.04% hydrogen, 0.84 % nitrogen, 0.19% sulphur, 0.071% chlorine.

Organic compounds from renewable raw materials like plant biomass are increasingly central to research in renewable energy and the circular economy. Biomass serves as a key feedstock for bioconversion, with microorganisms converting cellulose, hemicellulose, and lignin into bio-based products such as bioethanol, butanol, and acetone. Second-generation ethanol from lignocellulosic biomass offers a promising alternative to fossil fuels, thanks to its low cost, wide availability and reduced emissions. Its antiknock properties also enhance fuel efficiency. Ethanol production efficiency largely depends on the plant cell wall composition, particularly the ratios of cellulose, hemicellulose and lignin.

The results concerning the quality of the investigated lignocellulosic Brassicaceae substrates and their theoretical ethanol potential are presented in Table 2. Notably, the concentrations of cellulose and hemicellulose in the *Isatis tinctoria* substrate are significantly higher compared to the other species. The cellulose content is similar in the substrates of *Sinapis alba* and *Brassica napus*, while hemicellulose levels do not differ substantially between *Brassica napus* and *Bunias orientalis*. Among the studied species, the *Sinapis alba* substrate is particularly rich in hemicellulose. The concentrations of acid detergent lignin across all substrates are within optimal ranges and show no significant variation. This consistency may positively influence the digestibility and decomposition efficiency of the lignocellulosic biomass. The estimated theoretical ethanol potential from fermentable sugars averaged 473 L/t in *Isatis tinctoria* substrate, 449 L/t in *Sinapis alba* substrate, 433L/t in *Bunias orientalis* substrate, as compared with 430 L/t in *Brassica napus oleifera* substrate.

Table 2

The biochemical composition and the theoretical ethanol potential of biomass from the studied *Brassicaceae* species

Indices	*Brassica napus*	*Bunias orientalis*	*Isatis tinctoria*	*Sinapis alba*
Acid detergent fibre, g/kg DM	484	489	512	484
Neutral detergent fibre, g/kg DM	675	682	738	701
Acid detergent lignin, g/kg DM	83	86	88	83
Cellulose, g/kg DM	401	403	424	401
Hemicellulose, g/kg DM	191	193	226	217
Theoretical ethanol potential:	429.62	432.54	472.98	448.77
from hexose sugars, L/t ODM	298.62	300.16	316.96	299.93
from pentose sugars, L/t ODM	131.00	132.38	155.02	148.84

Several literature sources describe the composition of cell walls in the biomass from the studied *Brassicaceae* species. According to Petersson A. *et al.* (2007) the oilseed rape straw had 907 g/kg dry matter and its chemical composition was 27.3 % glucan, 15.0 % xylan, 2.7 % galactan, 2.0 % mannan, 2.2% arabinan, 14.2% Klason lignin, 9.6% ash, 10.1 % extractives, and 17.0 % residual. Barbash V. *et al.* (2011) found that *Brassica napus* stalks had 3.2% ash, 29.6 % pentosans, 37.7 % cellulose, 26.4% lignin, while *Bunias orientalis* stalks had 5.1% ash, 19.9 % pentosans, 34.3 % cellulose, 22.2% lignin. Dukarska, D. *et al.* (2011) remarked that chemical composition of white mustard straw was 36.70% cellulose, 21.10% lignin, 3.46% extraction substances, 5.60% mineral substances.

Greenhalf C.E. *et al.* (2012) determined that rapeseed straw had 37.55% cellulose, 31.37% hemicellulose, 21.30% lignin, 3.76% soluble, 6.02% ash. Potucek F. *et al.* (2014) studied the chemical composition of rapeseed straw found that stalks had 4.45% ash, 76.15 % holocellulose, 33.90 % cellulose, 28.83 % α-cellulose, 21.35% lignin, while valves of siliques contained 7.83% ash,71.59 % holocellulose, 28.35% cellulose, 25.73% α-cellulose, 14.14 % lignin. Kiro M. (2015) reported that rapeseed straw contained 72.28 % holocellulose, 45.39 % α-cellulose, 19.43 % lignin, 3.32 % soluble, 4.27% ash. Viel M. *et al.* (2018) remarked that the chemical characterization of agro-resources of rapeseed straw had the following indices: 53.06% cellulose, 18.13% hemicellulose, 9.63 % lignin, 17.68% soluble and 0.79% ash. Hajj Obeid M. *et al.* (2022) mentioned that the chemical composition of the rapeseed straws was 51.40-55.20% cellulose, 9.30-15.00% hemicellulose, 8.40-10.90 % lignin, 20.90-29.90% soluble and 0.40-0.90% inorganic materials. Chen, S *et al.* (2018) mentioned that Rapeseed after the seeds had been collected had 51.15 g/kg CP, 114.48 g/kg WSC, 33.07 g/kg ADF, 47.34 g/kg

NDF. Comlekcioglu1 N. *et al.* (2018) remarked that stalks from *Isatis tinctoria* had 4.9% ash, 67.1 % holocellulose, 48.5% α-cellulose, 23.9 % lignin and 4.9% extractives, while *Isatis buschiana* – 11.1% ash, 70.1 % holocellulose, 32.9% α-cellulose, 19.9 % lignin and 4.1% extractives. Akgül M. *et al.* (2018) canola stalks contain 72.10% holocellulose, 42.55% α-cellulose, 13.15% lignin and 8.2% ash. Guo T.X. and Liang K.W., 2025, determined that from the pre-treated rapeseed straw, under the best conditions the ethanol output can reach 12.2 g/L.

As the availability of traditional fossil-based energy sources continues to decline and the global energy demand steadily increases, the transition toward renewable energy alternatives is becoming more urgent and vital. One such promising renewable energy sources is the generation of biogas through anaerobic fermentation. This process is increasingly recognized as a sustainable energy solution with a wide array of environmental and socio-economic benefits. Biogas production plays a significant role in reducing greenhouse gas emissions, thereby contributing to climate change mitigation. Additionally, it aids in the destruction of harmful pathogens, promotes the recycling of nutrients, and can stimulate economic growth at both regional and local levels by creating jobs and supporting agricultural development. In biogas reactors, organic material derived from various sources, such as biomass, agricultural residues, organic waste, or wastewater, is biologically broken down in the absence of oxygen. This anaerobic digestion process results in the formation of biomethane (the primary energy component of biogas), along with carbon dioxide and other by-products such as hydrogen sulfide, ammonia, and digestate. While biomethane serves as a clean and renewable energy source, the resulting digestate is rich in nutrients and can be utilized as a valuable organic fertilizer in agriculture, further closing the loop in sustainable resource use.

The evaluation of several Brassicaceae plant substrates for their potential in biogas production is summarized in Table 3, which presents various quality indices relevant to anaerobic digestion. The analysis indicated that the carbon-to-nitrogen (C/N) ratios of the tested substrates ranged between 29 and 73. Of all the species examined, only the substrate derived from *Sinapis alba* demonstrated a C/N ratio that falls within the optimal range typically recommended for efficient anaerobic digestion, which enhances microbial activity and methane production. In terms of structural biomass composition, the concentration of acid detergent lignin (a component that affects biodegradability) was found to be between 83 and 88 grams per kilogram across the different Brassicaceae species. Meanwhile, the hemicellulose content ranged from 191 to 226 grams per kilogram. These compositional factors influence the efficiency of the anaerobic fermentation process and the resulting methane yields. The biochemical methane potential, which is a key metric for evaluating a substrate's capacity to generate methane, was observed to range from 232 to 268 litres per kilogram of organic dry matter. These values confirm that all tested Brassicaceae substrates are suitable candidates for use as co-substrates in biogas production systems. Notably, *Sinapis alba* exhibited the highest BMP value among the tested species, highlighting its superior potential as a feedstock for efficient biogas generation.

Table 3

The biochemical composition and the theoretical ethanol potential of biomass from the studied *Brassicaceae* species

Indices	*Brassica napus*	*Bunias orientalis*	*Isatis tinctoria*	*Sinapis alba*
Crude protein, g/kg DM	*58.00*	*76.30*	*38.30*	*98.80*
Nitrogen, g/kg DM	*9.30*	*12.22*	*6.10*	*15.80*
Ash, g/kg DM	*58.50*	*64.00*	*60.40*	*54.80*
Organic matter, g/kg DM	*941.50*	*936.00*	*939.60*	*945.20*
Carbon, g/kg DM	*456.00*	*452.4*	*443.60*	*456.40*
Carbon/nitrogen ratio	*49.00*	*37.08*	*72.72*	*28.89*
Acid detergent lignin, g/kg DM	*83.00*	*86.00*	*88.00*	*83.00*
Hemicellulose, g/kg DM	*191.00*	*193.00*	*226.00*	*217.00*
Biomethane potential, L/kg VS	*258.00*	*232.00*	*249.00*	*268.00*
Biomethane potential, L/kg DM	*243.00*	*223.00*	*234.00*	*253.00*

Multiple studies have provided data on the biomethane production potential of biomass from the examined Brassicaceae species. According to Petersson A. *et al.* (2007) the biogas yield from oilseed rape straw was 0.42 m^3/kg VS, while from winter rye straw was 0.36 m^3/kg VS and from faba bean straw 0.44 m^3/kg VS. Carchesio M. *et al.* (2014) noted that substrates derived from *Isatis tinctoria* plant in the anaerobic digestion test achieved net methane yield 153.1 l/kg VS, with

33% estimated degrees of conversion. Ţîţei V. (2016) reported that the gas forming potential of organic digestible matter of studied substrates from *Isatis tinctoria* varied from 438 l/kg to to 465 l/kg VS and methane yield from 242 to 251/kg VS. Gaballah E.S. *et al.* (2020) found that methane yield of in combined pretreatment of rapeseed straw substrate archived 305.7 L/kg VS, which was 77.84% higher than the untreated rape straw substrate. Ţîţei V. (2021, 2022 a,b) reported that the biochemical methane potential of fresh and ensiled biomass substrates from *Brassica napus* was 303-324 L/kg, but from *Sinapis alba* reached 273-330 L/kg organic matter and from *Crambe cordifolia* 254 L/kg organic matter. According to Guo T.X., and Liang K.W., 2025, under optimal conditions, the methane output of rapeseed strawcan can reach up to 365 L/kg of volatile solids. Witaszek K. *et al.* (2025) noted that straw substrates derived from *Brassica napus* contained 49.22-66.52% ADF, 59.52-80.99% NDF and methane yields varied from 86.69 to 202.06L/kg VS, while those from *Triticum aestivium* 45.95-52.84% ADF, 77.07-87.09% NDF and methane yields varied from 200.8 to 272.08L/kg VS.

CONCLUSIONS

The elemental composition and calorific values of the studied biomass samples demonstrated their suitability for solid biofuel production. Notably, *Brassica napus* and *Sinapis alba* showed the highest energy content in pellet form, with net calorific values ranging from 15.01 to 15.70 MJ/kg.

Sinapis alba met the optimal range recommended for anaerobic digestion, further reflected in its highest biochemical methane potential (268 L/kg ODM) among the evaluated species.

Isatis tinctoria dry biomass substrates are significantly higher concentrations of cellulose and hemicellulose and the estimated theoretical ethanol potential averaged 473 L/t.

Overall, *Sinapis alba* emerged as a highly versatile lignocellulosic feedstock, combining strong performance in both thermochemical (combustion, pelletization) and biochemical (bioethanol, biomethane) energy pathways. These findings support its integration into diversified bioenergy systems aimed at enhancing sustainability and resource efficiency.

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REFERENCES

Ababii A., Cerempei V., Ţîţei V., Guţu A., Cîrlig N., Gadibadi M., Mardari, L., Doroftei, V., Cozari, S., Andreoiu, A., Garștea, N., Mazăre, V., 2023- *Some seeds characteristic and biomass quality of some Brassicaceae and Fabaceae species in Moldova.* Scientific Papers. Series A. Agronomy, 66(1):645-654.

Abbasi-Riyakhuni, M., Hashemi, S. S., Denayer, J. F., Aghbashlo, M., Tabatabaei, M., & Karimi, K. (2025). Integrated biorefining of rapeseed straw for ethanol, biogas, and mycoprotein production. *Fuel*, *382*, 133751.

Alluvione F., Moretti B., Sacco D., Grignani C. 2011- *EUE (energy use efficiency) of cropping systems for a sustainable agriculture*. Energy, 36 (7): 4468–4481.

Akgül M., Erdönmez I., Çiçekler, M., Tutus A., 2018- *The investigations on pulp and paper production with modified kraft pulping method from canola (Brassica napus L.) stalks.* Kastamonu Univ., Journal of Forestry Faculty, 8 (3): 357-365.

Akter, M. M., Surovy, I. Z., Sultana, N., Faruk, M. O., Gilroyed, B. H., Tijing, L., Kabir, M. M. (2024). Techno-economics and environmental sustainability of agricultural biomass-based energy potential. *Applied Energy*, *359*, 122662.

Barbash V., Poyda V., Deykin I., 2011- *Peracetic acid pulp from annual plants.* Cellulose Chemistry and Technology, 45 (9–10): 613–618.

Carchesio M., Tatàno F., Lancellotti, I., Taurino, R.,Colombo, E., Barbieri, L., 2014 - *Comparison of biomethane production and digestate characterization for selected agricultural substrates in Italy.* Environmental Technology, 35:2212-2226.

Cástková T., Hýsek Š., Sikora A., Schönfelder O., Böhm M., 2018- *Chemical and physical parameters of different modifications of rape straw (Brassica napus L.).* BioResources, 13(1): 104-114.

Casau M.; Dias, M.F.; Matias, J.C.O.; Nunes, L.J.R., 2022- Residual Biomass: A Comprehensive Review on the Importance, Uses and Potential in a Circular Bioeconomy Approach. Resources 2022, 11, 35. https://doi.org/10.3390/ resources11040035

Chen S., Wan C., Ma Y., Zhang K., Wang F., Shen S., 2023- *Study on the quality of mixed silage of rapeseed with alfalfa or Myriophyllum.* International Journal of Environmental Research and Public Health, 20, 3884. doi.org/10.3390/ijerph20053884

Chico-Santamarta L., Humphries A.C., White D., Chaney K., Godwin R.J., 2009- *Effect of pre- and postpelletisation storage of canola (oilseedr ape) straw on the quality and properties of pellets.* ASABE Annual Meeting, no. 096105. 10.13031/2013.27054.

Chico-Santamarta L., Chaney K., Godwin R.J., White D.R., Humphries A., 2012- *Physical quality changes during the storage of canola (Brassica napus L.) straw pellets.* Applied Energy Journal, 95: 220-226.

Cîrlig N., Guţu A., Iurcu-Străistaru E., 2024- *Isatis tictoria L.– biological peculiarities and usage as honey plant.* In: Ştiinţa în Nordul Republicii Moldova: realizări, probleme, perspective, Chişinău, 445-449.

Cîrlig N., Ţîţei V., Guţu A., 2023- *High-value melliferous plant resources.* In. Instruire prin cercetare pentru o societate prosperă, Chişinău. 1: 172-175

Comlekcioglu N., Tutus A., Çiçekler M., Çanak A., Zengin G., 2016- *Investigation of Isatis tinctoria and Isatis buschiana stalks as raw materials for pulp and paper production.* Drvna Industrija. 67:249-255. 10.5552/drind.2016.1542

Cozari S., Ţîţei V., Guţu A., Andreoiu A.C., Coşman S., Coşman V., Mocanu N., Mardari L., 2022- *The quality of silage from Isatis tinctoria*. In: The scientific symposium Biology and Sustainable Development. Bacău. p. 84-85.

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.

Doroftei V., Ţiţei V., Ababil A., Blaj V., Cozari S., Andreoiu A.C., Maruşca T., Coşman V., Guţu A., 2021- *Evaluarea calităţii biomasei din plantaţiile semincere de ierburi perene şi posibilităţi de valorificare.* Genetica, fiziologia şi ameliorarea plantelor, Chişinău, 305-308.

Dukarska D., Bartkowiak M., Stachowiak-Wencek, A., 2015- *White mustard straw as an alternative raw material in the manufacture of particleboards resinated with different amounts of urea-formaldehyde resin*. Drewno, *58*(194):49-63.

Dukarska D., Łęcka J., Szafoni K., 2011- *Straw of white mustard (Sinapis alba) as an alternative raw material in the production of particle boards resinated with UF resin.* Acta Sci. Pol. Silv. Colendar. Rat. Ind. Lignar. 10(1) :19-28.

El-Araby R., 2024- *Biofuel production: exploring renewable energy solutions for a greener future.* Biotechnol Biofuels 17, 129 https://doi.org/10.1186/s13068-024-02571-9.

Fuksa P., Hakl J., Brant V., 2013- *Energy balance of catch crops production.* Zemdirbyste-Agriculture, 100(4):355–362.

Gageanu I., Cujbescu D., Persu C., Voicu G., 2018- *Influence of using additives on quality of pelletized fodder.* In. *Engineering for Rural Development*. 17: 1632-1638.

Gaballah E.S., Abomohra A.E.F., Xu C., Elsayed M., Abdelkader T.K., Lin J., Yuan Q., 2020- *Enhancement of biogas production from rape straw using different co-pretreatment techniques and anaerobic co-digestion with cattle manure.* Bioresource Technology. 309. 123311. 10.1016/j.biortech.2020.123311.

Gao Y., Wang X., Chen Y., Li P., Liu H., Chen H., 2017- *Pyrolysis of rapeseed stalk: Influence of temperature on product characteristics and economic costs*. Energy, 122: 482-491.

Goff B.M., Moore K.J., Fales, L., Heaton A., 2010- *Double-cropping sorghum for biomass.* Agronomy Journal, 102:1586-1592.

Greenhalf C.E., Nowakowski D.J., Bridgwater A.V., Titiloye J., Yates N., Riche A., Shield I., 2012- *Thermochemical characterisation of straws and high yielding perennial grasses*. Industrial Crops and Products, 36:449–459.

Gudîma A., 2017- *Evaluarea utilizării reziduurilor agricole pentru scopuri energetice. Studiu de caz pentru raionul Soroca, Republica Moldova.* Meridian ingineresc, 1: 26-29. I

Guo T.X., Liang K.W., 2025- *Bioenergy production from rapeseed straw: a feasibility study*. Journal of Energy Bioscience, 16(4): 163-171.

Habashescu I., Cerempel V., 2012- *Energetic potential of vegetable mass in agriculture of Republic of Moldova*. International conference "Energy of moldova –regional aspects of development", 355-359.

Hajj Obeid M., Douzane O., Freitas Dutra L., Promis G., Laidoudi B., Bordet F., Langlet T., 2022- *Physical and mechanical properties of rapeseed straw concrete.* Materials, 15(23):8611. DOI: 10.3390/ma15238611

Heneman P., Červinka J. 2007- *Energy crops and bioenergetics in the Czech Republic.* Annals of Warsaw University of Life Sciences – SGGW Agriculture (Agricultural Engineering), 51: 73-78.

Jankowski K.J., 2025- *White mustard: energy balance at different nitrogen management strategies*. Industrial Crops and Products, 225, 120420. https://doi.org/10.1016/j.indcrop.2024.120420

Kachel M., Kraszkiewicz A., Subr A., Parafiniuk S., Przywara A., Koszel M., Zając G., 2020- *Impact of the type of fertilization and the addition of glycerol on the quality of spring rape straw pellets.* Energies, 13(4), 819. https://doi.org/10.3390/en13040819

Karaosmanoglu F., Tetik E., Gollu E., 1999- *Biofuel production using slow pyrolysis of the straw and stalk of the rapeseed plant.* Fuel Processing Technology, 59:1-12.

Kiro M., 2015- *Cellulose fibers extracted from agricultural biomass.* Tekstilna industrija, 62(4): 15-19.

Kord B., Zare H., Hosseinzadeh A., 2016- *Evaluation of the mechanical and physical properties of particleboard manufactured from canola (Brassica napus) straws.* Maderas. Ciencia y tecnología. 18(1): 9 – 18. 10.4067/S0718-221X2016005000002.

Liang K.W, Yan S.D., 2025- *Exploring the potential of rapeseed biomass for renewable energy*. Journal of Energy Bioscience, 16(3): 105-116

Marian G., 2014- *Managementul biomasei agrosilvice pentru scopuri energetice.* Chişinău: 264 p.

Marian G., Ianuş G., Istrate B., Banari A., Nazar B., Munteanu C., Măluţan T., Gudima A., Ciolacu F., Daraduda N., Paleu V., 2022- *Evaluation of agricultural residues as organic green energy source based on seabuckthorn, blackberry, and straw blends*. Agronomy, 9(12):1-14. DOI: *https://doi.org/10.3390/agronomy12092018*

Maroušek J., 2013- *Study on commercial scale steam explosion of winter Brassica napus straw.* International Journal of Green Energy, 10: 944–951.

Maj G., Krzaczek P., Stamirowska-Krzaczek E., Lipińska H., Kornas R., 2019- *Assessment of energy and physicochemical biomass properties of selected forecrop plant species.* Renewable Energy, 143:520-529.

Naveed M.H., Nouman M., Khan A., Mukarram M., Raza Naqvi S., Abdullah A., & *Ul Haq Z., Ullah, H., Mohamadi H., 2024-* *Cellulosic biomass fermentation for biofuel production: Review of artificial intelligence approaches.* Renewable and Sustainable Energy Reviews. 189. 113906. 10.1016/j.rser.2023.113906.

Niedziółka I., Kachel-Jakubowska M., Kraszkiewicz A., Szpryngiel M., Szymanek M., ZAKLIKA B., 2015- *Assessment of quality and energy of solid biofuel production*. Bulgarian Journal of Agricultural Science, 21 (2):461–466

Pavlenco A., Marian G., Gudîma A., 2018- *Potenţialul energetic al reziduurilor agricole: studiu de caz pentru regiunea de dezvoltare nord, Republica Moldova.* Ştiinţa Agricolă, 2-:141-149.

Petersson A., Thomsen M.H., Hauggaard-Nielsen H., Thomsen A.B., 2007- *Potential bioethanol and* *biogas production using lignocellulosic biomass from winter rye, oilseed rape and faba bean.* Biomass and Bioenergy, 31(11–12):812–819.

Plištil D., Brožek M., Malaák J., Roy A., Hutla P., 2005- *Mechanical characteristics of standard fuel briquettes on biomass basis*. Research in Agricultural Engineering, 51(2):66-72.

Potucek F., Gurung B., Hájková K., 2014- *Soda pulping of rapeseed straw.* Cellulose Chemistry and Technology, 48 (7-8):683-691

Rahim M., Douzane O., Le A.T., Promis G., Langlet T., 2015- *Characterization and comparison of hygric properties of rape straw concrete and hemp concrete.* Construction and Building Materials, 102:679–687.

Rozenfelde, L., Puke, M., Vedernikovs, N., Scherbaka, R., Rapoport, A. (2021). Catalytic treatment of rapeseed straw for enhanced production of furfural and glucose for bioethanol production. *Process Biochemistry*, *102*: 102-107.

Stasiak M., Molenda M., Bańda M., Wiącek J., Parafiniuk P., Gondek E., 2017- *Mechanical and combustion properties of sawdust—straw pellets blended in different proportions*. Fuel Processing Technology, 156:366-375.

Stolarski M.J., Welenc M., Krzyżaniak M., Olba-Zięty E., Stolarski J., Wierzbicki S., 2024- *Characteristics and changes in the properties of cereal and rapeseed straw used as energy feedstock.* Energies, 17*(5),* 1243. https://doi.org/10.3390/en17051243

Stolarski M.J, Rybczyńska B., Krzyżaniak M., Lajszner W., Graban Ł., Peni D., Bordiean A., 2019- *Thermophysical properties and elemental composition of agricultural and forest solid biofuels versus fossil fuels.* Jorunal of Elementology, 24(4): 1215-1228. DOI: 10.5601/jelem.2019.24.1.1819

Stolarski M. J., Krzyżaniak M., Olba-Zięty E., 2025- Properties of pellets from forest and agricultural biomass and their mixtures. *Energies*, *18*(12), 3137. https://doi.org/10.3390/en18123137

Teleuta A. S., 1989a- *Biochemical characteristics of mustard green mass in Moldovan conditions.* In. Abstracts of reports of the 2nd All-Union Seminar of Young Scientists and Specialists on New Forage Crops. Odessa, p. 15. [in Russian].

Teleuta A., 1989b- *Energy and nutritional value of spring turnip rapeseed in Moldovan conditions.* In. Abstracts of reports of the 2nd All-Union Seminar of Young Scientists and Specialists on New Forage Crops. Odessa, p. 52 [in Russian].

Teleuta A. S., Cretu L.G. 1989- *Feeding qualities of spring rape green mass in Moldovan conditions.* In. Feed plant resources - a factor of scientific and technical progress in forage production. Kyiv – Belaya Tserkov, p. 35. [in Russian].

Ţîţei V., 2016- *Agrobiological peculiarities and prospects for valorification of woad, Isatis tinctoria L., in Moldova.* Lucrări Ştiinţifice, seria Agronomie, 59 (2):267-272.

Ţîţei V., 2022a- *Calitatea silozului din unile specii din familia Brassicaceae și posibilități de valorificare în Republica Moldova.* Știința și inovarea în nordul Republicii Moldova: probleme, realizări, perspective. Bălți, 277-281.

Ţîţei V., 2021- *The quality of fresh and ensiled biomass of Brassica napus oleifera and prospects of its use.* Scientific Papers. Series A. Agronomy, 64(2):330–335.

Ţîţei V., 2022b- *The quality of fresh and ensiled biomass from white mustard, Sinapis alba, and its potential uses.* Scientific Papers. Series A. Agronomy, 65(1): 559-566.

Ţîţei V., Roşca I., 2021- *Bunele practici de utilizare a terenurilor degradate în cultivarea culturilor cu potenţial de biomasă energetică (Good practices for the use of degraded lands in crop cultivation with a potential of energetic biomass).* In Romanian. Chişinău, 80p.

Vergun O., Rakhmetov, D., Shymanska, O., Rakhmetova S., Bondarchuk O., Fishchenko, V.. 2021-*Morphometric and biochemical features of different Bunias orientalis L. genotypes in the M. M. Gryshko National Botanical Garden of the NAS of Ukraine.* Plant Varieties Studying and Protection, 17: 66-72. 10.21498/2518-1017.17.1.2021.228213.

Viel M., Collet F., Lanos C., 2018- *Chemical and multi-physical characterization of agro-resources' by-product as a possible raw building material*. Industrial Crops and Products, 120:214–237. doi: 10.1016/j.indcrop.2018.04.025.

Witaszek K., Kupryaniuk K., Kupryaniuk J., Panasiewicz J., Czekała W., 2025- *Optimization of straw particle size for enhanced biogas production: a comparative study of wheat and rapeseed straw.* Energies, 18*(7),* 1794. https://doi.org/10.3390/en18071794

Yang B., Na N., Wu N., Sun L., Li, Z.; Qili M., Han H., Xue Y., 2024- *Impact of additives and packing density on fermentation weight loss, microbial diversity, and fermentation quality of rape straw silage.* Microorganisms 12*,* 1985. *https://doi.org/10.3390/microorganisms12101985*

Ye Y., Guo W., Ngo H.H., Wei W., Cheng D., Bui X.T., Hoang N.B., Zhang H., 2024- *Biofuel production for circular bioeconomy: Present scenario and future scope.* Science of The Total Environment, 935:172863. doi: 10.1016/j.scitotenv.2024.172863.

Zabaniotou A., Ioannidou O., Skoulou V., 2008- *Rapeseed residues utilization for energy and 2nd generation biofuels.* Fuel, 87(8-9):1492-1502.

Zarajczyk, J., 2013- *Technical and technology conditions of plant biomass pellets for energy purposes.* Monografi e i rozprawy. Inżynieria Rolnicza, 1 (142), 2:81.