OPTIMIZING FUEL ROLLS FROM CROP RESIDUES USING COMPREHENSIVE QUALITY INDICATOR (CQI)

Svitlana Yaheliuk, Mihailo Fomich
Lutsk National Technical University, Ukraine
cler2010@gmail.com, mykhailo.fo@gmail.com

Abstract. The efficient utilization of crop residues as fuel rolls (solid fuel) holds significant potential for advancing renewable energy systems, reducing agricultural waste, and mitigating environmental impacts. However, the variability properties of such materials require a comprehensive assessment framework to ensure consistent fuel quality. This research focuses on optimizing the quality of fuel rolls made from crop residues by developing a Comprehensive Quality Indicator (CQI). This CQI integrates multiple parameters, including such properties as moisture content, fuel roll density, as well as the calorific value, ash content and emission levels. Each parameter is normalized against established benchmarks and weighted according to its impact on overall fuel performance. The weights are determined using a combination of expert judgment and analytic hierarchy processes. Experimental validation was performed on fuel rolls produced from various crop residues, such as wheat straw and flax stems. Key physical properties were measured using standard methods: moisture content was determined via oven-drying, and ash content through muffle furnace incineration. Combustion properties, including flue gas composition, were assessed using a gas analyser. These measured values were normalized and aggregated into CQI. The results demonstrated the effectiveness of the CQI framework in distinguishing high-quality fuels from suboptimal ones. Furthermore, sensitivity analysis identified the moisture content, calorific value, and emission levels as critical factors influencing fuel quality, highlighting specific areas for optimizing crop residue processing. This research contributes to the advancement of environmental and economic sustainability by providing a scientifically robust and scalable method for assessing and improving the quality of fuel rolls produced from crop residues.

Keywords: comprehensive quality indicator, fuel rolls, crop residues, environmental sustainability.

Introduction

Agricultural waste burning remains a serious environmental problem, causing air pollution, loss of organic matter, and a reduction in soil fertility. Scientists in India and South Asia [1; 2] confirm the negative impact of this phenomenon, including greenhouse gas emissions and deterioration of ecosystem functions. Instead, efficient processing of crop residues can be an environmentally and economically viable alternative.

Crop residues, especially flax stems that remain after harvesting with modern technologies [3] can be used to produce a variety of products, including feed, compost and biofuels [4]. However, among all the options, the production of solid biofuels is the most rational solution. Scientists from Scotland and Saudi Arabia [5] explore the possibilities of processing flax stems, particularly in the form of fuel rolls, which have the potential to become an effective source of renewable energy.

The use of agricultural residues as a raw material for biofuels contributes to reducing dependence on fossil fuels and lowering CO_2 emissions. Studies [5; 6] have shown that flax fuel rolls have desirable characteristics, such as high density, low ash content, and good mechanical strength. The properties of other fuels have also been investigated [7]. However, the optimal biomass composition for the formation of fuel rolls remains understudied.

An important aspect according to European researchers is determining sustainable collection rates for agricultural residues to produce biofuels, as excessive extraction can negatively affect the soil quality and the balance of organic carbon [8-10]. Organizations such as IEA Bioenergy (USA) emphasize the need to combine energy efficiency with environmental safety during biofuel production [11].

To assess and optimize the quality of fuel rolls, a Comprehensive Quality Indicator (CQI) is proposed, which takes into account the following parameters: moisture content, density, calorific value, ash content, and emission levels. Each parameter is normalized according to established standards, and its importance is determined based on expert assessments and the method of hierarchical analysis.

The purpose of this study is to develop a Comprehensive Quality Indicator (CQI) for the assessment and optimization of the composition of fuel rolls made from agricultural residues. This will contribute to increasing the energy efficiency and environmental sustainability of biofuels, as well as enhancing Ukraine's energy independence in the face of modern challenges [12]. The results of this work will help develop a scientifically sound and practically applicable methodology for assessing the quality of fuel

DOI: 10.22616/ERDev.2025.24.TF106

rolls. The results of this research align with the National Waste Management Strategy in Ukraine until 2030 [13].

Materials and methods

A batch of compact fuel rolls of various compositions was manufactured on specially designed equipment. The study examined three different variants of fuel rolls, each with distinct proportional compositions of raw materials. Table 1 summarizes the fuel roll variants used in the experiments.

Table 1

Fuel roll variants

Variant	Proportional composition of components, %		Fuel roll type	Fuel roll image
	Flax stems	Wheat, rye		
1	75	25	1R75/25	
2	50	50	2R50/50	
3	25	75	3R25/75	

The fuel rolls were burned in a small, metal combustion chamber equipped with manual fuel loading (Fig. 1, a). During the combustion experiments, the qualitative and quantitative composition of the flue gas emissions was continuously monitored for each variant of the fuel rolls. A portable gas analyser, Testo 340 (Fig. 1, b), was employed for this purpose [14]. This device is equipped with all the necessary features to study the combustion parameters of fuel rolls and can be used in harsh environmental conditions. Key physical properties were measured using standard methods: moisture content was determined via oven-drying (ISO 18134-1:2022, (ISO 18134-2:2024), and ash content through muffle furnace incineration (EN ISO 18122:2022).

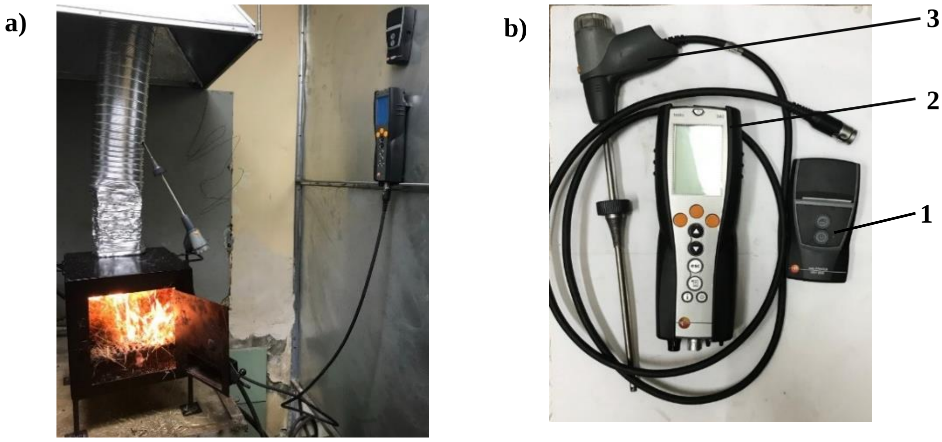

Fig. 1. **Experimental equipment for combustion testing of fuel rolls from crop residues:** a – combustion chamber with a gas analyser; b – gas analyser Testo 340 (1 – control unit; 2 – analyser unit; 3 - measuring probes)

A standard method was used to determine the Comprehensive Quality Indicator (CQI) [15, 16]. The CQI is determined using multi-criteria normalization and weighting, according to the following theoretical model:

$$CQI = \sum_{i=1}^{n} W_i \times P_i , \tag{1}$$

where W_i – weight of parameter i, reflecting its influence on the overall fuel quality;
P_i – normalized score for parameter i scaled to a dimensionless range (0-1).

The weight of parameters was determined using an expert method [17]. This method involves engaging specialists to assess the significance of each parameter influencing the overall fuel quality. A panel of five experts was formed, including specialists in bioenergy, agricultural engineering, environmental science, and biomass processing. The experts were selected based on their professional and scientific qualifications, experience in biomass utilization, and prior involvement in similar research projects. A list of parameters requiring evaluation is created, along with descriptions of their impact on the fuel quality. The benchmark values were selected based on high-performance solid fuels (e.g. oak biomass).

Experts rated the significance of each parameter on a predefined scale (e.g. 1 to 10). The collected evaluations are processed to determine the average rating or median for each parameter. The individual expert rating S_{ij} for parameter *i* given by expert *j* is aggregated as:

$$S_i = \frac{1}{m}\sum S_{ij}, \tag{2}$$

where S_i – average score of parameters i;
S_{ij}– score assigned by the expert *j*;
m – number of experts.

The obtained scores are then normalized so that the sum of all weight coefficients equals 1. The weight of each parameter W_i is calculated as

$$W_i = \frac{S_i}{\sum S_i}. \tag{3}$$

The degree of agreement among expert opinions is analysed using statistical methods.

The normalized score P_i for the parameter *i* is calculated to scale its value into a dimensionless range between 0 and 1. The normalization formula depends on the correlation between the parameter value and fuel quality:

Direct Correlation (higher is better) for parameters where a higher value means better quality:

$$P_i = \frac{MeasuredValue}{BenchmarkValue}, \tag{4}$$

where *MeasuredValue* – actual value obtained from experiments;
BenchmarkValue – standard or reference value for optimal fuel quality.

Inverse Correlation (lower is better) for parameters where a lower value means better quality:

$$P_i = \frac{BenchmarkValue}{MeasuredValue}. \tag{5}$$

The research was conducted in the boiler room of the Lutsk National Technical University (LNTU), utilizing solid fuel rolls produced from raw materials cultivated on the university experimental plots. This setup ensured direct control over both the cultivation conditions and the subsequent processing of agricultural residues into fuel rolls, enabling a more precise evaluation of their combustion characteristics under controlled conditions. To ensure the reliability of the results, each measurement was performed in triplicate, and the average value was recorded. The standard deviation and the coefficient of variation were calculated to assess repeatability. All instruments were calibrated before use.

Results and discussion

The study confirms that converting agricultural residues into solid biofuels not only mitigates environmental hazards associated with open burning but also contributes to energy independence. The CQI framework developed herein provides a reliable and scientifically sound method for assessing fuel rolls from crop residues.

The experimental results obtained for different fuel roll compositions are shown in Table 2. It should be noted that the thermal efficiency values vary between the options and the emissions tend to decrease with increasing proportion of flax stems. Nine key parameters – Moisture Content, Thermal Efficiency, Ash Content, Density and Emission Levels (CO_2, O_2, CO, SO_2, NOx) were evaluated by five experts. These scores were averaged and then normalized so that their sum equals 1. Calculations were made using formulas (2), (3) and the importance of each parameter was determined. Table 2 lists the final weight (W_i) coefficients for each parameter based on expert evaluation S_i.

The benchmark value for each parameter was compared against the measured values for three fuel roll variants: 1R75/25, 2R50/50, and 3R25/75. Depending on whether a parameter's correlation with quality is direct (higher is better) or inverse (lower is better), the normalized score P_i was computed using either the ratio of the measured value to the benchmark value (4) or the benchmark value to the measured value (5).

Table 2

Experimental results of fuel roll quality assessment

No.	Parameter	Bencmark value	Measured value			W_i	Correlation
			1R75/25	1R50/50	1R25/75		
1	Moisture content, %	10	11	10	9	0.06	Inverse
2	Thermal efficiency value, Gcal·hr^{-1}	0.388	0.420	0.394	0.367	0.20	Direct
3	Ash content, %	2.7	2.3	1.8	1.8	0.12	Inverse
4	Density, kg·m^{-3}	600	140	130	120	0.03	Direct
Emission levels:							
5	CO_2, %	8.2	8.61	7.7	6.8	0.12	Inverse
6	O_2, %	9.6	9.0	10.3	11.5	0.16	Inverse
7	CO, ppm	2604	2131	1210	950	0.14	Inverse
8	SO_2, ppm	47	52	44	38	0.03	Inverse
9	NOx, ppm	75	68	62	57	0.16	Inverse

Using the weight coefficients (Table 2) and the normalized scores (computed via formulas (4) and (5)), the Comprehensive Quality Indicator (CQI) for each fuel roll variant was calculated according to equation (1). The final CQI values are summarized in Table 3.

Table 3

Comprehensive Quality Indicator (CQI) for fuel roll variants

Fuel roll Type	Proportional composition of components, %	CQI value
1R75/25	75% Flax stems, 25% Wheat/Rye	0.85
2R50/50	50% Flax stems, 50% Wheat/Rye	0.98
3R25/75	25% Flax stems, 75% Wheat/Rye	1.05

The study applied the Comprehensive Quality Indicator (CQI) to evaluate and compare different fuel roll compositions. The CQI values obtained for the tested variants – 0.84 for 1R75/25, 0.98 for 2R50/50, and 1.05 for 3R25/75 – highlight the overall effectiveness of these fuel rolls. The 3R25/75 composition achieved the highest CQI, indicating that it provides the best balance between combustion efficiency and emission levels.

The weighting system applied in the CQI assessment revealed that even moderately weighted parameters, such as ash content, CO emissions, and NOx emissions, have a substantial impact on the final quality rating when they deviate significantly from benchmark values. This underscores the importance of comprehensive optimization, ensuring that no individual parameter compromises the overall performance of the fuel rolls.

The 3R25/75 variant demonstrated the best performance due to its lower levels of ash content, CO, and NOx emissions while maintaining acceptable values for the moisture content and thermal efficiency. This highlights the critical role of balancing combustion parameters with environmental parameters to achieve an optimal fuel composition.

Moisture levels directly influence the combustion efficiency and emissions. The tested fuel rolls exhibited acceptable moisture content, contributing to stable combustion performance. The thermal efficiency values showed minimal variation across different fuel roll compositions.

While the sulfur content was slightly higher than that of oak firewood, the total emissions (CO and NOx) were significantly lower. This makes the tested fuel rolls an environmentally friendly option, reducing harmful air pollutants compared to conventional wood fuels.

Although the density of these fuel rolls is lower than that of traditional wood, it remains within an acceptable range for efficient combustion. The slightly reduced density may influence storage and handling but does not diminish the fuel's practical usability.

One of the most compelling advantages of these fuel rolls is their sustainability and renewability. As they are made from agricultural residues rather than primary forest resources, they contribute to waste reduction and circular economy principles. Additionally, their lower total emissions, compared to both fossil fuels and traditional firewood, reinforce their environmental benefits.

From a practical standpoint, the adoption of these fuel rolls could significantly reduce dependency on wood-based biomass, particularly in rural and agricultural regions. Their cost-effectiveness and availability further enhance their attractiveness as a viable alternative fuel.

Conclusions

The resulting CQI values were 0.84, 0.98, and 1.05 for 1R75/25, 2R50/50, and 3R25/75 variants, respectively. Notably, the 3R25/75 composition attained the highest CQI, indicating superior overall performance among the tested samples. Contributing factors to this outcome include relatively favorable values for ash content, CO, and NOx emissions, as well as acceptable moisture content and thermal efficiency.

Although the density of these fuel rolls is lower compared to that of conventional wood fuels and the sulfur content is slightly higher than that found in oak firewood, the overall emissions are lower. This suggests that the fuel rolls, despite being produced from agricultural residues, provide a balanced profile of combustion efficiency and environmental performance. The lower density, while potentially affecting handling and storage, does not compromise the overall quality as indicated by CQI. Instead, it reflects the nature of the raw materials used, which are residues rather than purpose-grown biomass.

The weighting scheme employed in calculating CQI reveals that even moderately weighted parameters, such as density and sulfur content, can significantly influence the final indicator if their values deviate substantially from the benchmarks. Therefore, for further optimization, it is crucial to control the moisture content and enhance the combustion efficiency. Improvements in compaction techniques to increase the density of fuel rolls could also be beneficial, provided that emission levels remain within acceptable limits.

Author contributions

Conceptualization, M.F; methodology, S.Y.; software, S.Y.; validation, M.F; formal analysis, M.F; investigation, M.F; data curation, M.F and S.Y.; original draft preparation, V.B.; writing – review and editing, M.F and S.Y.; visualization, M.F and S.Y.; project administration, S.Y. All authors have read and agreed to the published version of the manuscript.

References

[1] Lin M., BeghoT. Crop residue burning in South Asia: A review of the scale, effect, and solutions with a focus on reducing reactive nitrogen losses. Journal of Environmental Management, vol. 314, 2022, 115104, [online] [20.01.2025]. Available at DOI: 10.1016/j.jenvman.2022.115104.
[2] Patel S., Singh A., Litoria P., Sood A., Kaur S., Pateriya B. Development of a Crop Residue Burning Information and Management System using Geo-Spatial Technologies, vol. 15, 2021, pp. 61-67.
[3] Yukhymchuk S., Yukhymchuk Sv., Tolstushko M., Tolstushko N. Checking performance of disc-belt flax pulling apparatus. Proceedings of 23rd International Scientific Conference "Engineering for Rural Development", Vol. 23, May 22-24, 2024, Jelgava, Latvia, pp. 351-356.

[4] Ali M., Saleem M., Zakir K., Watson I. The use of crop residues for biofuel production. Biomass, Biopolymer-Based Materials, and Bioenergy, Woodhead Publishing, 2019, pp. 369-395. DOI: 10.1016/B978-0-08-102426-3.00016-3

[5] Yaheliuk S., Didukh V., Busnyuk V., Boyko G., Shubalyi O. Optimization on efficient combustion process of small sized fuel rolls made of oleaginous flax residues. INMATEH – Agricultural Engineering, vol. 62(3), 2020. pp. 361-368. DOI: 10.35633/inmateh-62-38

[6] Didukh V., Yaheliuk S. Artyukh T Albota D Holiy O Decrease of elastic properties of oleanginous flax residues by decortication. INMATEH-Agricultural Engineering. 67(2), pp. 2022, pp. 285-292 DOI: 10.35633/inmateh-67-29

[7] Bratishko V., Tkachenko T., Shulga S., Tigunova O., Chemical studies of parameters and composition of lignocelluloseraw material samples of municipal origin. Proceedings of 23rd International Scientific Conference "Engineering for Rural Development", Vol. 23, May 22-24, 2024, Jelgava, Latvia, pp. 1008-1015.

[8] Yaheliuk S., Fomych M., Rechun O. Global market trends of grain and industrial crops. Commodity Bulletin, 17(1), 2024. pp. 134-145. DOI: 10.62763/ef/1.2024.134

[9] Waste generation by classification groups of the state classification of waste in 2020. Official website of State Statistic Service of Ukraine. [online] [20.02.2025]. Available at: https://ukrstat.gov.ua/operativ/operativ2018/ns/uv_zaklass/arch_uv_zaklass_e.htm.

[10] Geletukha G.G., Zheliezna T., Matveev Y., Kucheruk P., Drahniev S., Kramar V., Zubenko V., Bashtovyi A., Haidai O.I., Radchenko S., Pastukh A., Tryboi O.V. Energy production from biomass in Ukraine: technologies, development and prospects. 2022. (In Ukrainian). DOI: 10.15407/akademperiodyka.464.373.

[11] Mobilisation of agricultural residues for bioenergy and higher value bio-products: Resources, barriers and sustainability. IEA Bioenergy 2017, 124 p, [online] [21.01.2025]. Available at: https://www.ieabioenergy.com/wp-content/uploads/2018/01/TR2017-01-F.pdf?utm_source=chatgpt.com

[12] Moshenskyi S., Grytshen D., Petruk O. Agricultural and resourse economy of Ukraine and problems for economic growth. Scientific Horizons, 27(1), 2024. pp. 152-161. doi: 10.48077/scihor1.2024.152.

[13] Національна стратегія управління відходами в Україні до 2030 року. (National Waste Management Strategy in Ukraine until 2030 (In Ukrainian) [online] [04.04.2025]. Available at: https://zakon.rada.gov.ua/laws/show/820-2017-%D1%80#Text

[14] Інструкція Testo 340 (Testo 340 manual (In Ukrainian) [online] [04.04.2025] https://www.testo.kiev.ua/docs/docs_new/testo-340_Man_UA.pdf?srsltid = AfmBOorZhPrd03SxtfXe96w02cNoLGqCtbN5CvCufm3ySF4b7wk9d9pA

[15] Світлишин І. І. Методичний підхід до оцінювання якості продукції. Економіка, управління та адміністрування, Svitlyshyn, I. I. Methodological approach to product quality assessment. Economics, management and administration, (1(103), 2023. pp 64-69 [online] [22.02.2025]. pp. 64-69. (In Ukrainian). DOI: 10.26642/ema-2023-1(103)-64-69

[16] Сатир Л. М., Задорожна Р. П., Непочатенко А. В., Кепко О. І. Аналітичний кваліметричний підхід до оцінки якості продукції як інструмент прийняття ефективних стратегічних рішень. Інвестиції: практика та досвід. (Satyr, L., Zadorozhna, R., Nepochatenko, A., Kepko, O. Analytical qualimetric approach to product quality assessment as a tool for making effective strategic decisions. Investments: practice and experience.) 2021. № 17. pp. 18–24. (In Ukrainian) DOI: 10.32702/2306-6814.2021.17.18

[17] Сахно В. П., Біліченко В. В., Іванушко О. М., Визначення вагових коефіцієнтів для побудови математичної моделі коректування періодичності проведення технічного обслуговування і ремонту. (Sakhno, V., Bilichenko, V., Ivanushko, M., Determination of weight coefficients for building a mathematical model of adjusting the periodicity of technical maintenance and repair). VMT, Vol. 2, 2017. Pp. 141-149 (In Ukrainian) [online] [21.02.2025]. Available at: https://vmt.vntu.edu.ua/index.php/vmt/article/view/109