Received: 27.02.2026 | Revision: 12.03.2026 | Accepted:29.03.2026 | Published: 12.09.2026

Technical Sciences

doi: 10.31210/spi2026.29.02.28
UDC 536.626.1, 631.572
ORIGINAL ARTICLE

Scientific Progress & Innovations
ISSN: 2786-8842 (Print)
2786-8850 (Online)

29 (2)
2026

Determination of the lower calorific value of biomass using mechatronic system elements

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Article info

Citation: Padalka, V., Gorbenko, O., Kulyk, M., & Chumak, M. (2026). Determination of the lower calorific value of biomass using mechatronic system elements. *Scientific Progress & Innovations*, 29(2), 205–210. doi: 10.31210/spi2026.29.02.28

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Achieving environmental sustainability requires an immediate transition to energy-saving technologies and renewable energy sources. It has been confirmed that, in addition to classical renewable sources (solar, hydro, wind, and geothermal energy), plant biomass represents a valuable raw material. It enables the sustainable production of biofuels, providing an alternative to fossil fuels. This role of biofuels determines the need for a thorough study and justification of the energy characteristics of relevant renewable agricultural crops. Plant biomass, which includes wood and shrubs of various species, possesses distinctive fuel properties that can be described by well-known parameters such as the heat of combustion (higher and lower calorific values), ash melting characteristics, ash content, and chemical composition. The presented generalization represents a new scientific contribution aimed at developing a methodology and conducting experimental and comparative studies to determine the relative indicators of the calorific value of organic plant-based samples using original and more affordable equipment with elements of mechatronic systems. The dry plant material of each energy crop was analyzed using a laboratory device – a "biofuel analyzer." The original laboratory setup was manufactured in accordance with applicable technical regulations. The research showed that the results of calorific value measurements of plant biomass obtained with the developed laboratory setup, equipped with mechatronic measuring components, were in good agreement with the data obtained using a standard bomb calorimeter. This consistency is confirmed by statistical significance ($LSD_{0.05}$ at $p<0.05$). Under the experimental conditions, the calorific value of six plant-based material samples was determined as follows: Castor bean (*Ricinus communis*) – 9.78 MJ/kg; Sorghum (*Sorghum*) – 17.97 MJ/kg; Switchgrass (*Panicum virgatum*) – 14.71 MJ/kg; Paulownia (*Paulownia*) – 10.67 MJ/kg; Virginia mallow (*Sida hermaphrodita*) – 13.93 MJ/kg; and Sorrel hybrid (*Rumex patientia* × *Rumex tianschanicus*) – 12.35 MJ/kg.

Keywords: biomass, measurement, lower calorific value, energy crops, mechatronic measurement systems.

Визначення нижчої теплоти горіння зразків рослинного походження засобами з елементами мехатронних систем

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Досягнення екологічної стійкості вимагає негайного переходу до енергозберігаючих технологій та відновлюваних джерел енергії. Підтверджено, що, окрім класичних відновлюваних джерел (сонячна, водна, вітрова та геотермальна енергія), біомаса рослин є цінною сировиною. Вона дає змогу стало виробляти біопаливо, пропонуючи альтернативу викопним видам палива. Саме ця роль біопалива зумовлює необхідність глибокого вивчення та обґрунтування енергетичних характеристик відповідних відновлюваних сільськогосподарських культур. Рослинна біомаса, яка охоплює деревину та чагарники різних порід, має відмінні паливні властивості, які можна описати відомими показниками – теплотою згоряння (вищою та нижчою), характеристиками плавлення золи, зольністю, хімічним складом тощо. Наведене узагальнення становить нове наукове рішення, що полягає у розробленні методики та проведенні дослідницьких і порівняльних експериментів із визначення відносних показників теплотворної здатності органічних зразків рослинного походження з використанням оригінального та більш доступного обладнання з елементами мехатронних систем. Рослинну суху сировину кожної з енергетичних культур аналізували на лабораторній установці – «біопаливному аналізаторі». Оригінальна лабораторна установка була виготовлена відповідно до чинних технічних регламентів. Дослідження показали, що результати вимірювань теплотворної здатності рослинної біомаси, отримані на розробленій лабораторній установці з використанням вимірювальних засобів з елементами мехатронних систем, добре узгоджуються з даними, одержаними за допомогою стандартної калориметричної бомби. Це підтверджується статистичною значущістю ($LSD_{0.05}$ при $p<0,05$). В умовах експерименту було визначено теплотворну здатність шести зразків матеріалу рослинного походження: рицина (*Ricinus communis*) – 9,78 МДж/кг; сорго (*Sorghum*) – 17,97 МДж/кг; світчграс (*Panicum virgatum*) – 14,71 МДж/кг; павловнія (*Paulownia*) – 10,67 МДж/кг; сіда (*Sida hermaphrodita*) – 13,93 МДж/кг; щавнат (*Rumex patientia* × *Rumex tianschanicus*) – 12,35 МДж/кг.

Ключові слова: біомаса, вимірювання, нижча теплота згорання, енергетичні рослини, мехатронні системи вимірювання.

Бібліографічний опис для цитування: *Падалка В. В., Горбенко О. В., Кулик М. І., Чумак М. В.* Визначення нижчої теплоти горіння зразків рослинного походження засобами з елементами мехатронних систем. *Scientific Progress & Innovations*. 2026. № 29 (2). С. 205–210.

Introduction

Energy consumption is a fundamental requirement for the existence and development of human civilization [1]. Throughout history, access to energy has been critically important for meeting human needs and improving the quality of life. Most scientific studies are focused on finding ways to reduce energy consumption, particularly in the agro-industrial sector [2–4].

However, the rapid growth of industry over the last centuries has led to a significant increase in energy consumption, which in turn exhausts global reserves of fossil fuels – even under the most optimistic estimates, these resources will last for only about 100 years [5, 6]. Therefore, achieving environmental sustainability requires an urgent transition to energy-saving technologies and renewable energy sources.

A number of studies [7–10] confirm that, in addition to conventional renewable sources (solar, hydropower, wind, and geothermal energy), plant biomass is a valuable raw material for sustainable biofuel production, offering an alternative to fossil fuels. The strategic role of biofuels necessitates an in-depth examination and justification of the energy characteristics of agricultural crops.

A significant proportion of raw materials for biofuel production is derived from agricultural crops. In particular, grain crops such as wheat, barley, corn, oats, and rye, as well as starch-containing plants (potatoes, sugar beet), are used for obtaining bioethanol via fermentation [11, 12]. Simultaneously, grain straw represents a promising solid biomass for direct combustion or pyrolysis [13].

Furthermore, oilseed crops such as rapeseed, sunflower, flax, and mustard, as well as less common species (hemp, safflower, castor bean), serve as sources of oil, which can be converted into biodiesel through transesterification [14, 15]. The use of non-edible oilseed crops is also considered as a strategy to reduce competition with food crops [16]. These approaches enable the integration of plant biomass into energy systems as a renewable resource.

To objectively assess the efficiency and stability of any energy crop, it is necessary to determine key energy indicators such as energy consumed, energy produced, and energy balance. According to studies [17], the energy balance of an agricultural crop is best evaluated through a comprehensive analysis of all physical and thermal characteristics of the resulting plant-based biological material.

Therefore, the development of a methodology for investigating the lower heating value (LHV) of plant-derived samples is a relevant task for addressing the challenge of identifying alternative renewable energy sources – both in Ukraine and worldwide.

The aim of the study

The aim of the research is to develop a methodology and conduct experimental and comparative investigations to determine the relative calorific values of organic plant-derived samples using equipment equipped with elements of mechatronic systems.

Materials and methods

Methodology of Comparative Research on the Characteristics of Organic Plant-Based Samples.

Plant biomass, which includes wood and shrubs of various species, possesses diverse fuel-related properties [18, 19]. These can be described using several well-known characteristics, such as: higher and lower heating value, ash melting behavior (ash content), chemical composition (content of key elements influencing the toxicity of gaseous emissions during combustion), particularly chlorine, carbon, hydrogen, nitrogen, and sulfur; moisture content (relative and absolute); hardness and density; amount of gaseous products; solid carbon content; ash composition and percentage; and slagging tendencies of ash, particulate matter, and biological spores, among others.

According to the general objectives of the research, the laboratory setup enables the assessment of several thermal process parameters [20], particularly the lower heating value (LHV) and ash content during combustion of plant-based biological material samples.

Ash content refers to the percentage of non-combustible residue (on a dry mass basis) formed from the mineral impurities in the fuel during complete combustion and is expressed as a percentage.

The ash content of a dry plant-based sample is determined using the following formula:

$$X^{p} = \frac{M_{t2}}{M_{t}} \cdot 100\%, \quad (1)$$

where M_t is the mass of the tested material sample, kg;

M_{t2} is the mass of ash of the tested material sample, kg.

The ash mass M_{t2} is determined as the difference between the total ash residue obtained after combustion and the mass of the combustible material used to initiate the combustion process (M_{st2}), which is measured after each experiment.

The ash content recalculated to the absolutely dry sample is determined as follows:

$$X^{A} = \frac{M_{t2}}{M_{t}(100 - W_{t})} \cdot 100\%, \quad (2)$$

where W_t is the moisture content of the tested material, %.

The mass of ash M_{t2} is also determined as the difference between the total ash residue after combustion and the ash mass of the auxiliary combustible material used to initiate the combustion process (M_{st2}), which is measured after each test.

The relative moisture content W_t of the tested material is determined using the standard thermal method.

Prerequisites for Laboratory Investigations:

1. The tested material, according to its physicochemical properties, belongs to the class of low-flammability substances. Therefore, at the initial stage, it is necessary to expose the sample to an open flame. The heat released by the ignition material must be taken into account when determining the calorific value of the sample.

2. During combustion, the tested material releases energy over time according to a nonlinear characteristic.

This process is an important operational parameter for energy systems using such material as fuel, and therefore it must be studied in the time domain.

3. The lower heating value (LHV) of organic plant-based samples is determined through experimental measurement of the amount of heat accumulated by the energy-absorbing liquid during the combustion of a specific mass of the sample.

4. To ensure the reliability of the obtained results, calibration tests using materials with known calorific properties must be performed. This makes it possible to determine the instrumentation error coefficient of the experimental setup, taking into account the following factors: efficiency of heat transfer to the energy carrier; heat transferred to the setup and its structural elements; heat consumed for preheating the air and sample; heat losses due to evaporation of the energy-absorbing liquid; other uncontrolled factors.

5. The research is conducted to experimentally determine the lower heating value (LHV) of organic plant-derived samples.

6. The research is also aimed at experimental comparison of operational combustion characteristics of fuels produced from mixtures of plant-based organic samples.

The design layout of the laboratory setup for experimental determination of the lower heating value and comparative characteristics of organic plant-derived samples is presented in ***Figure 1***.

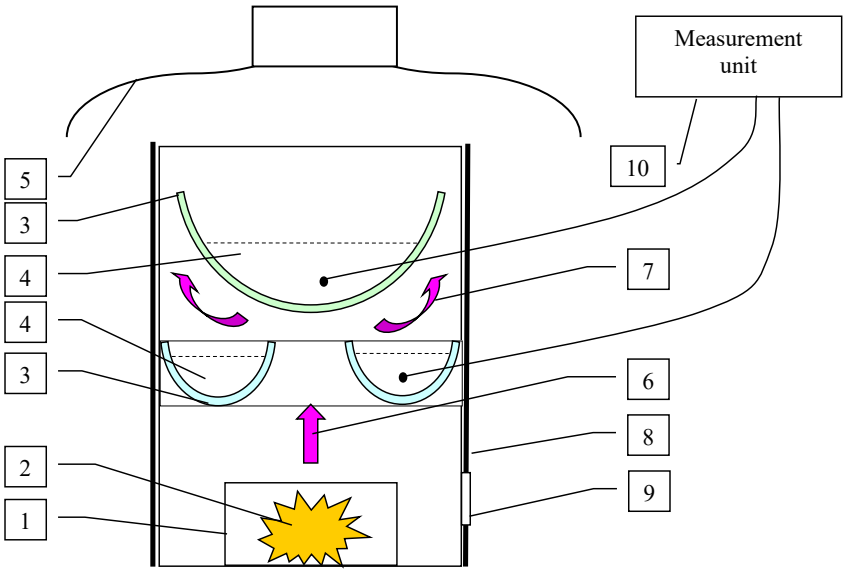

Fig. 1. Laboratory setup diagram

1 – heat-resistant container; 2 – test sample with ignition initiator; 3 – cascade-arranged cups; 4 – energy-accumulating liquid; 5 – exhaust hood; 6, 7 – flows of preheated air and combustion gases; 8 – housing of the laboratory setup; 9 – loading window; 10 – measurement unit.

The laboratory setup (***Fig. 1***) operates as follows. The test material sample (2) together with the ignition initiator is placed inside the container (1) made of heat-resistant material. The corresponding cups (3), arranged in a cascade configuration, are installed and filled with the energy-accumulating liquid (4) after determining its volume.

To ensure maximum efficiency of heat transfer, the thermal flow streams (6, 7) are directed around the cups, which are arranged according to a cascade pattern. To remove combustion products from the laboratory environment, the housing of the setup (8), made of thermo-insulating material, is placed under an exhaust hood (5).

Ignition of the sample with the initiator is performed through the loading window (9). The temperature rise of the energy-accumulating liquid is recorded using the measurement unit (10) [20], equipped with thermocouples, and the data are registered digitally with a time-based sampling frequency for further analytical processing.

Calibration procedure and measurement error determination.

The purpose of the calibration procedure is to determine the heat of combustion of the material used to initiate ignition of the test sample, as well as to estimate the overall measurement error of the developed laboratory setup.

At the first stage of calibration research, the calorific value of the ignition material is experimentally determined under actual laboratory operating conditions. The following sequence of steps is performed:

1. The cups (3) (***Fig. 1***) are filled with the energy-accumulating liquid (4) in volumes Vp_1 and Vp_2, depending on their number. The electronic measurement module with mechatronic system elements is activated, recording the temperature values measured by thermocouples in the following locations: ambient air temperature (Tp_1); combustion gas temperature inside the exhaust hood (Tp_2); temperature of the energy-accumulating liquid in each cup (Tn_1(t) and Tn_2(t)). The ignition material – ethyl alcohol (96%) of predefined mass Mst – is placed inside the setup.

2. Through the loading window (9), the ignition material (96% ethanol) is ignited. The exhaust hood (5) is activated to evacuate combustion gases from the laboratory environment. The duration of the experiment is determined by the complete combustion of the sample.

3. Upon completion of combustion, the measurement unit is switched off. The obtained data are automatically

transmitted to the computing device and saved into the dataset. Subsequently, the ash residue (M_{st2}) and the remaining mass of the sample after combustion (M_{t2}) are measured using analytical scales.

4. To ensure reliable measurement accuracy, each experiment is repeated five times.

5. The specific calorific value of the ignition material is determined using the following formula:

$$Q_{st} = \frac{c \cdot \rho_p \left[V_{p1} \cdot (T_{p1n} - T_{p11}) + V_{p2} \cdot (T_{p2n} - T_{p21})\right]}{M_{st}}, \quad (3)$$

where Q_{st} is the specific heat of combustion of the ignition substance, J/kg;

c is the specific heat capacity, J/(kg·°C) (for water under ambient conditions, 4183 J/(kg·°C));

V_{p1}, V_{p2} are the volumes of the energy-accumulating liquid in each cup, m³;

q_p is the density of the energy-accumulating liquid under ambient conditions, kg/m³ (for water, 1000 kg/m³);

T_{pni} is the temperature of the energy-accumulating liquid at the end of the experiment, °C;

T_{pn1} is the temperature of the energy-accumulating liquid at the beginning of the experiment, °C;

M_{st} is the mass of the combustible material used to initiate the combustion of the test sample, kg.

The overall coefficient of instrumental error in the measurement of the heat of combustion is determined by comparison with known reference values. For 96 % ethanol, the heat of combustion is 30 MJ/kg, according to the following formula:

$$k_{inst} = \frac{Q_{ststat}}{Q_{tabl}} \quad (4)$$

The determined coefficient of instrumental error must be taken into account when processing the results of absolute measurements.

To assess the energy efficiency of biomass production from energy crops, the author's methodology by Kalinchenko O. V. and Kulyk M. I. was applied. Statistical analysis of the obtained data was performed using established methods, considering the experiment replications.

Results and discussion

The dry plant-based raw material of each energy crop was analyzed using a prototype of the laboratory *biofuel analyzer*. The original laboratory setup was manufactured in accordance with established technical regulations (***Fig. 2***, ***Fig. 3***).

Fig. 2. Laboratory setup (external view)
5 – exhaust hood; 8 – housing of the laboratory setup; 9 – loading window; 10 – measurement unit.

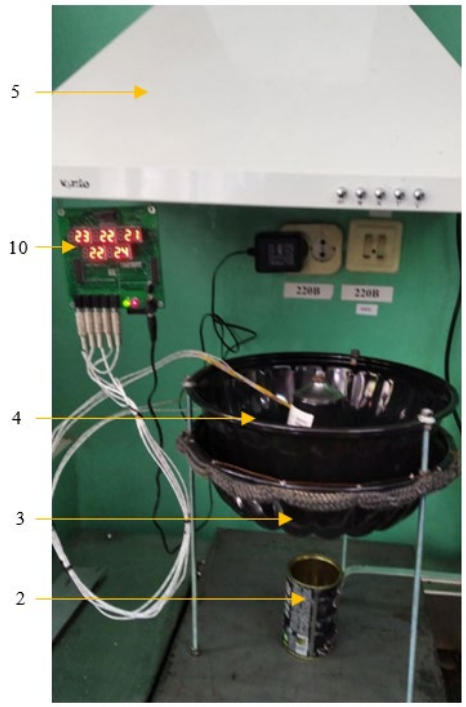

Fig. 3. Laboratory setup (without thermal casing)
2 – container for the test sample with ignition initiator; 3 – cascade-arranged cups; 4 – energy-accumulating liquid; 5 – exhaust hood; 10 – measurement unit.

The results of the calibration tests and the experimentally determined heat of combustion of the ignition initiator under laboratory conditions are presented in ***Table 1***.

Table 1
Data for calculating the heat of combustion of the ignition substance

Experiment	V_{p1}, m³	V_{p2} m³	T_{p11} °C	T_{p21} °C	T_{p1i} °C	T_{p2i} °C	M_{st} kg	q_p kg /m³	c, kJ/kg °C	Q_{st}, MJ/kg	Q_{stat}, MJ/kg
1	0.0015	0.0015	22	22	33	27	0.0052	1000	4183	21,7	
2	0.0015	0.0015	31	25	42	32	0.0051	1000	4183	21,8	
3	0.0015	0.0015	21	22	33	27	0.0053	1000	4183	21,8	21.9
4	0.0015	0.0015	32	26	43	33	0.005	1000	4183	22,1	
5	0.0015	0.0015	31	25	42	32	0.0051	1000	4183	22,1	

The coefficient of instrumental error is calculated using Equation (4), k_{inst} = 21.9 / 30.0 = 0.73.

Considering the obtained coefficient, the evaluation of parameters for the plant-based samples of the selected energy crops was carried out.

Based on the results of the laboratory studies, the ash content and the lower heating value (LHV) of all selected samples of energy crops were determined.

Ash content directly influences the operational performance of fuel and is regulated by international European and American standards. The obtained results indicate that the ash content values generally meet these requirements; however, further investigation under real production conditions is necessary.

Using the analysis of the experimental data, a methodology for determining the lower heating value of energy crops was proposed. Compared with widely known methods, the described equipment is original and suitable for implementation in laboratories focused on operational studies of biofuel under production conditions.

The developed methodology for determining energy indicators allows calculating fuel demand and cost when compiling thermal balances and assessing the operating characteristics of systems using plant-based fuel.

During the determination of the calorific value of plant raw materials from energy crops, the following results were obtained (***Table 2***), which were compared with the results obtained using the established laboratory method – the calorimetric bomb.

Table 2
Calorific value of plant-based raw materials, MJ/kg

Plant biomass	Laboratory setup	Calorimetric bomb	Deviation
Castor bean *(Ricinus communis)*	9,78	9,92	0,02
Sorghum *(Sorghum)*	17,97	17,94	-0,03
Switchgrass *(Panicum virgatum)*	14,71	14,72	0,01
Paulownia *(Paulownia)*	10,67	10,69	0,02
Virginia mallow *(Sida hermaphrodita)*	13,93	13,90	0,03
Sorrel hybrid *(Rumex patientia × Rumex tianschanicus)*	12,35	12,33	0,02
$LSD_{0.05}$	–	–	0,003

Conclusions

The study presents a generalization and proposes a new solution to a scientific problem, which consists in the development of a methodology and the implementation of experimental and comparative investigations to determine the relative calorific values of organic plant-derived samples using original equipment equipped with elements of mechatronic systems.

The research demonstrated that the calorific value measurements of plant biomass carried out using the developed laboratory setup with mechatronic measuring instruments are in agreement with the results obtained using a standard calorimetric bomb. Since the obtained data were statistically identical – as confirmed by their significance level ($LSD_{0,05}$ at $p < 0,05$) – this justifies the use of the original biofuel analyzer as a reliable tool for the objective determination of the energy characteristics of plant raw materials.

Under experimental conditions, the calorific value of six plant-based samples was determined as follows: Castor bean (*Ricinus communis*) – 9.78 MJ/kg; Sorghum (*Sorghum*) – 17.97 MJ/kg; Switchgrass (*Panicum virgatum*) – 14.71 MJ/kg; Paulownia (*Paulownia*) – 10.67 MJ/kg; Virginia mallow (*Sida hermaphrodita*) – 13.93 MJ/kg; Sorrel hybrid (*Rumex patientia* × *Rumex tianschanicus*) – 12.35 MJ/kg.

Future research in the cultivation of bioenergy crops should be directed towards the economic and social justification of their use, including an assessment of the feasibility of employing non-food agricultural lands and areas of non-agricultural enterprises, in order to avoid competition with food production systems.

DECLARATIONS

Ethical Statement
Not applicable.

Funding
This research received no external funding.

Conflict of Interest
The authors declare no conflict of interest.

Acknowledgements
None.

Declaration of AI and AI-assisted technologies
The authors declare that no artificial intelligence or AI-assisted technologies were used in the preparation of this manuscript.

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