UDK 620.92:543.42:658.562 DOI 10.36910/775.24153966.2026.85.32

С.В. Ягелюк

Луцький національний технічний університет

СПЕКТРОФОТОМЕТРИЧНІ МЕТОДИ ОЦІНЮВАННЯ ЯКОСТІ БІОПАЛИВА ІЗ СТЕБЕЛ ЛЬОНУ ОЛІЙНОГО: ЗНАЧЕННЯ ДЛЯ СТАЛОГО РОЗВИТКУ

Дослідження присвячене розробленню спектрофотометричної методики оцінювання біопаливних матеріалів, отриманих із некондиційних стебел льону олійного (Linum usitatissimut L.). Досліджено брикети твердого біопалива з різним співвідношенням біомаси льону та зв'язуючого – сапропелю (L70/S30, L50/S50, L100), а також контрольний зразок на основі деревини. Водні витяжки продуктів згоряння аналізували методом спектрофотометрії в діапазоні довжин хвиль 200–1100 нм. Отримані спектри пропускання продемонстрували подібний загальний характер для всіх зразків, що свідчить про близькі структурні особливості продуктів згоряння. Для всіх досліджених зразків встановлено наявність вираженого мінімуму при довжині хвилі 975 нм. Ця спектральна особливість пов'язана з другим обертоном валентних коливань O–H і відображає наявність гідроксилвмісних сполук та зв'язаної води в досліджуваних системах. Порівняльний аналіз показав, що відмінності значень пропускання між біопаливами на основі льону та контрольним деревним зразком не перевищують 3–4 %, що свідчить про високий ступінь подібності їхнього хімічного складу продуктів згоряння. Використання сапропелю як зв'язуючого не призводить до істотної зміни загальних спектральних характеристик, однак зумовлює підвищення інтенсивності поглинання через більший вміст мінеральних компонентів. Отримані результати підтверджують доцільність використання біомаси стебел льону олійного для виробництва твердих біопалив та демонструють, що спектрофотометричний аналіз може бути застосований як експрес-метод оцінювання їх якості та екологічної безпечності.

Ключові слова: *спектрофотометричний аналіз; спектроскопія; продукти згоряння; лігноцелюлозна біомаса; утилізація аграрних відходів; сапропель як зв'язуюче; спектральні маркери; оцінювання якості палива*

S. Yaheliuk

SPECTROPHOTOMETRIC METHODS FOR QUALITY ASSESSMENT OF BIOFUEL MATERIALS DERIVED FROM OIL FLAX STEMS: IMPLICATIONS FOR SUSTAINABLE DEVELOPMENT

The study is devoted to the development of a spectrophotometric methodology for evaluating biofuel materials produced from non-conditioned oil flax (Linum usitatissimum L.) stems. Solid biofuel briquettes with different ratios of flax biomass and sapropel binder (L70/S30, L50/S50, L100) and a control wood sample were investigated. Aqueous extracts of combustion residues were analyzed using spectrophotometry in the wavelength range of 200–1100 nm. The obtained transmission spectra demonstrated similar overall patterns for all samples, indicating comparable structural features of combustion residues. A pronounced minimum at a wavelength of 975 nm was identified for all investigated samples. This spectral feature is attributed to the second overtone of O–H stretching vibrations and reflects the presence of hydroxyl-containing compounds and bound water in the analyzed systems. Comparative analysis showed that the differences in transmission values between flax-based biofuels and the control wood sample do not exceed 3–4%, indicating a high degree of similarity in the chemical composition of their combustion residues. The use of sapropel as a binder does not significantly affect the overall spectral characteristics, although it increases absorption intensity due to higher mineral content. The results confirm the feasibility of using oil flax stem biomass for the production of solid biofuels and demonstrate that spectrophotometric analysis can be applied as a rapid diagnostic tool for assessing their quality and environmental safety.

Keywords: *spectrophotometric analysis; spectrophotometry; combustion residues; lignocellulosic biomass; agricultural waste valorization; sapropel binder; spectral markers; biofuel quality assessment*

Introduction. The growing demand for renewable energy and sustainable resource utilization has intensified interest in solid biofuels derived from agricultural residues. Among these, oil flax (Linum usitatissimum L.) stems represent a promising but insufficiently utilized type of biomass generated in significant amounts after harvesting and primary processing of the crop. Efficient conversion of such non-conditioned biomass into solid fuels requires not only technological solutions but also scientifically substantiated approaches to assessing their quality and environmental safety [1, 2]. Solid biofuel briquettes based on lignocellulosic materials, including flax stems, are extensively studied in the context of renewable energy production due to their availability, renewability, and potential to substitute conventional fossil fuels. Their combustion behavior is determined by physicochemical properties of the raw material, including composition, density, moisture content, and the presence of binders [3, 4]. Natural binders such as sapropel are of particular interest, as they enhance the structural integrity and mechanical stability of briquettes without significantly reducing calorific value. However, the addition of such components may influence the composition of combustion residues, thus requiring detailed analytical evaluation [5]. Traditional methods for evaluating solid biofuels include calorimetric analysis, determination of ash content, volatile matter, and elemental composition. Although these methods provide integral characteristics of the fuel, they do not allow detailed assessment of changes in the chemical structure of combustion products. In this context, spectrophotometric methods offer an alternative analytical approach, enabling the study of optical properties of combustion products and providing information on their chemical composition based on wavelength-dependent absorption or transmission spectra [6].

Spectrophotometry is widely used in chemical and environmental analysis due to its sensitivity and rapid response. It allows the identification of characteristic spectral features associated with specific functional groups or compounds in liquid extracts [7]. However, its application to the assessment of combustion residues of solid biofuels remains limited, particularly for biomass derived from flax stems. The identification of reproducible spectral patterns may serve as a basis for the development of rapid methods for assessing the quality of solid biofuels.

Despite significant research on biomass combustion and biofuel characterization, there is a lack of systematic approaches that utilize spectrophotometric analysis to evaluate the environmental safety and compositional similarity of combustion residues from different biofuel compositions. In particular, the identification of stable spectral markers common to various types of biomass-based fuels remains an unresolved scientific problem. Therefore, the aim of this study is to develop a spectrophotometric methodology for evaluating solid biofuel materials produced from non-conditioned oil flax stems based on the analysis of transmission spectra of combustion residue extracts, as well as to identify characteristic spectral features that can serve as reliable indicators of fuel quality and environmental safety.

Analysis of recent studies. Recent international studies show that agricultural residues are increasingly regarded as a valuable raw material for renewable energy production, especially in the form of densified solid biofuels. General reviews emphasize that biomass can partly replace fossil fuels, but its practical use depends on the availability of stable feedstocks, appropriate preprocessing, and reliable methods for quality assessment [1], [2]. In this context, densification is considered one of the key technological routes because it improves bulk density, handling, transportability, and combustion performance of plant-derived fuels [3], [4].

A large part of the foreign literature is devoted to the technological factors that determine the quality of densified biofuels. Researchers have shown that the strength and durability of briquettes and pellets depend on particle size, moisture content, compaction pressure, temperature, and the natural binding ability of lignocellulosic components [3]. Review studies also note that densification systems must be adapted to the physical nature of the raw material, since different agricultural residues behave differently during compaction and combustion [4]. This is especially important for flax residues, which are structurally heterogeneous and mechanically different from wood-based biomass.

Another important line of recent research concerns the broader performance of densified biomass fuels, including storage, transportation, end-use efficiency, and market applicability. A later review confirms that the long-term viability of densified solid biomass depends not only on energy properties, but also on technical reliability and user acceptance in practical energy systems [5]. Thus, the literature increasingly moves from general biomass potential toward the integrated evaluation of final fuel products.

At the same time, the body of studies specifically focused on oil flax residues remains much smaller than the general biomass literature. This gap is important because flax residues have specific elastic and structural properties that complicate their processing into compact fuel forms. In particular, Didukh et al. showed that oleaginous flax residues are characterized by pronounced elasticity and rapid shape recovery, which hinder their technological processing, while decortication reduces elasticity and improves the suitability of the biomass for further utilization [8]. This result is directly relevant to fuel production, because reduced elasticity facilitates compaction and helps stabilize the geometry and density of the final solid fuel.

Further development of this research direction is presented in studies devoted to the production of fuel rolls from agricultural stem biomass. Yaheliuk et al. demonstrated that the density of fuel rolls can be optimized through the rational selection of chamber pressure, biomass moisture, and holding time, confirming the importance of controlling technological parameters during fuel formation [9]. In an earlier study, the same research group showed that the combustion efficiency of small-sized fuel rolls made of oleaginous flax residues depends on roll diameter, density, and moisture content; in addition, combustion tests indicated environmentally acceptable performance under properly selected operating conditions [10]. Together, these studies establish the engineering basis for converting flax residues into solid fuels, but they are focused mainly on production and combustion parameters rather than on the analytical characterization of combustion residues.

A broader economic and resource-use context is also relevant. Analysis of global market trends for grain and industrial crops indicates the growing importance of integrated utilization of agricultural raw materials and residues, including non-food biomass streams [11]. At the national level, the Waste Management Strategy of Ukraine until 2030 also supports more efficient use of waste and secondary raw materials, providing an institutional framework for the valorization of agricultural residues into value-added products, including biofuels [12]. These considerations strengthen the relevance of research aimed at converting non-conditioned flax stems into energy materials instead of treating them as low-value waste.

Despite the considerable progress in biomass densification and combustion studies, the reviewed literature shows that much less attention has been paid to spectrophotometric assessment of combustion residues from flax-based solid biofuels. Most available works focus on feedstock properties, densification conditions, or combustion efficiency [3, 5, 8, 10], whereas analytical approaches for evaluating ash or extract composition through optical spectra are discussed much less frequently in the specific context of flax-derived fuels. Therefore, there is a clear need for a methodology that would complement engineering studies of briquetting and combustion with instrumental assessment of combustion residue extracts. Such an approach may improve comparative evaluation of different briquette compositions and provide an additional basis for judging their environmental safety and similarity to conventional solid fuels.

Thus, the analysis of the reviewed literature indicates that the issues of biomass utilization potential, densification of plant materials, and optimization of combustion processes are relatively well developed. However, methods for spectrophotometric evaluation of combustion residues of solid biofuels produced specifically from non-conditioned oil flax stems remain insufficiently studied. This determines the relevance and necessity of the present research.

The aim of this study is to develop a spectrophotometric methodology for evaluating the quality and environmental safety of solid biofuel materials produced from non-conditioned oil flax stems based on the analysis of transmission spectra of combustion residue extracts, as well as to identify characteristic spectral features that can serve as reliable indicators of fuel properties. The subject of the research is the spectrophotometric characteristics of transmission spectra of aqueous extracts obtained from combustion residues of solid biofuel briquettes with different component compositions.

Materials and Methods. The study was carried out using solid biofuel briquettes produced from non-conditioned oil flax (Linum usitatissimum L.) stem biomass. The investigated samples differed in the ratio of flax straw to binder (frozen sapropel): L70/S30 (70% flax biomass and 30% sapropel), L50/S50 (50% flax biomass and 50% sapropel), L100 (100% flax biomass without binder), and a control sample (D) based on wood biomass. Sapropel was selected as a natural binder due to its ability to enhance the structural integrity of briquettes without significantly reducing their calorific value, while its potential influence on combustion products requires detailed analytical evaluation (Fig. 1a). After combustion of the briquettes under controlled conditions, ash residues were collected and used for further analysis. Aqueous extracts of the combustion residues were prepared by mixing a fixed mass of ash residue with distilled water, followed by settling and filtration to obtain clear solutions suitable for spectrophotometric measurements. The prepared extracts were placed in standard optical cuvettes. The prepared aqueous extracts are presented in fig. 1b.

Spectral measurements were performed using a single-beam scanning spectrophotometer (UNICO 2800) operating in transmission mode (T%). The scanning was carried out in the wavelength range of 200–1100 nm. Prior to sample measurements, baseline correction was performed using a blank solution (distilled water) to eliminate background absorption effects. The spectrophotometric measurements were performed using the equipment shown in Fig. 2. The cuvette with the blank solution was placed in the optical path, and the baseline spectrum was recorded, after which the cuvette containing the sample extract was inserted and spectral scanning was conducted.

The scanning parameters were selected according to the instrument capabilities: the scanning step was set to 5 nm for general spectral acquisition and reduced when higher resolution was required, while the scanning speed was adjusted depending on the required resolution. The obtained spectra represent the dependence of light transmission (T%) on wavelength relative to the baseline, allowing comparative analysis of the investigated samples.

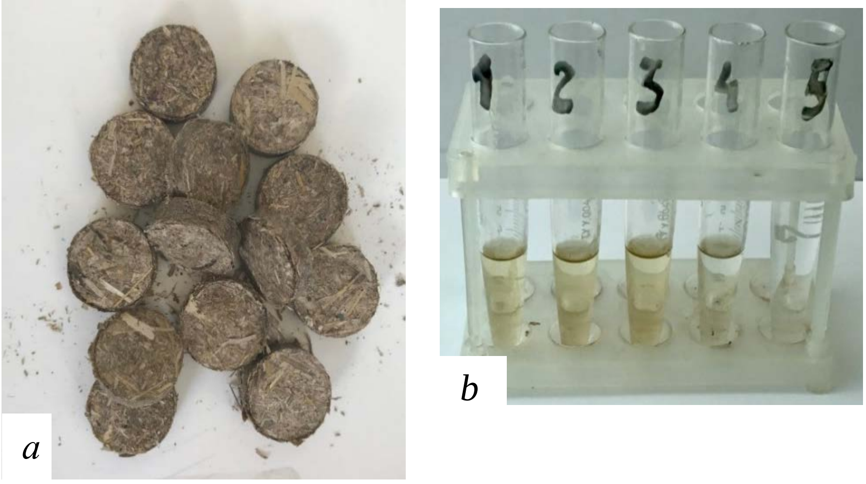

Fig. 1. **Biofuel samples and products of their analytical preparation: a – solid biofuel briquettes produced from oil flax stems; b – aqueous extracts of combustion residues obtained from solid biofuel samples**

Fig. 2. **Spectrophotometer UNICO 2800 used for spectral analysis of combustion residue extracts**

The spectral data were processed by identifying local maxima and minima of transmission and determining the corresponding wavelengths using the built-in peak search function of the spectrophotometer. Comparative analysis of spectral curves was performed to detect common patterns and characteristic features across all investigated samples, with particular attention to the identification of stable spectral extrema. This approach enabled the evaluation of similarities and differences in the chemical composition of combustion residues and provided a basis for assessing the quality and environmental safety of solid biofuel materials derived from oil flax stems in comparison with conventional wood-based fuels.

Results. The spectrophotometric analysis of aqueous extracts obtained from combustion residues of solid biofuel briquettes revealed consistent spectral patterns across all investigated samples. The spectra recorded in the wavelength range of 200–1100 nm demonstrated a similar overall shape, indicating the presence of structurally related components in the combustion residue extracts. The transmission spectra of aqueous extracts of combustion residues are presented in Fig. 3. As shown in Fig. 3, all spectra are characterized by smooth curves with several local extrema, which is typical for complex multicomponent systems formed after thermal decomposition of lignocellulosic materials. In the short-wavelength region (200–400 nm), a sharp decrease in transmission is observed for all samples, approaching near-zero values. This behavior is associated with strong absorption of ultraviolet radiation by conjugated organic structures and degradation products of lignocellulosic biomass [13], [14].

In the visible region (approximately 400–800 nm), transmission increases significantly and forms a relatively stable plateau. The spectral curves of all samples are close to each other in this region, although slight differences in transmission levels can be observed. These variations reflect differences in the concentration of absorbing components but do not allow reliable attribution to specific individual compounds, which is typical for multicomponent systems [15].

In the near-infrared region (800–1100 nm), more pronounced spectral features are observed. In particular, slight shifts in local extrema occur in the range of 870–910 nm. The L50/S50 sample shows a shift toward longer wavelengths (around 910 nm), whereas other samples demonstrate extrema closer to 870–895 nm. These variations can be attributed to changes in the mineral composition and structural environment of combustion residues, particularly in samples with increased sapropel content [16].

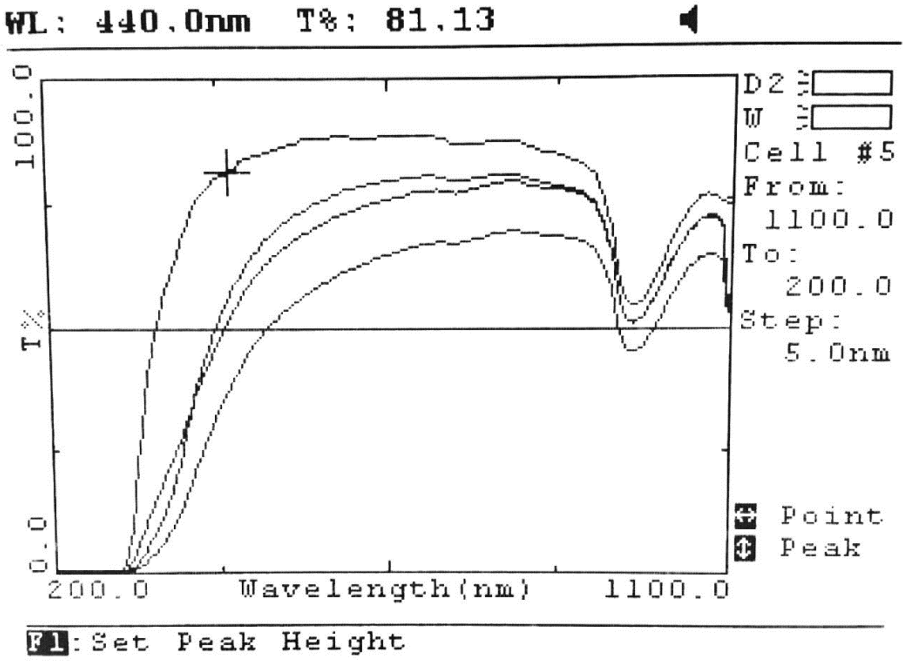

Fig. 3. **Transmission spectra of aqueous extracts of combustion residues of solid biofuel samples based on oil flax stems with different binder content (L70/S30, L50/S50, L100) and control sample (D) in the wavelength range of 200–1100 nm**

The most significant and consistent feature of all investigated spectra is the presence of a pronounced minimum at a wavelength of 975 nm. This minimum is observed for all samples regardless of their composition, indicating a common absorption mechanism. The transmission values at this wavelength are 51.19% for L70/S30, 45.41% for L50/S50, 51.03% for L100, and 54.63% for the control wood sample.

The spectral feature at 975 nm can be attributed to the second overtone of O–H stretching vibrations, which is characteristic of hydroxyl-containing compounds and bound water in complex systems [15], [17]. The reproducibility of this spectral feature across all samples indicates that it can be considered a diagnostic spectral marker for evaluating solid biofuel materials.

A comparative analysis shows that the differences in transmission values between flax-based samples and the control wood sample do not exceed 3–4%, indicating a high degree of similarity in the chemical composition of combustion residues. At the same time, the L50/S50 sample exhibits the lowest transmission value (45.41%), suggesting a higher concentration of absorbing components, which can be attributed to the increased content of mineral components introduced by the sapropel binder.

At longer wavelengths (around 1070 nm), all samples demonstrate an increase in transmission, indicating reduced absorption and confirming that the dominant absorbing components are active in the shorter near-infrared region. The characteristic spectral extrema identified for all investigated samples are summarized in Table 1.

The data presented in Table 1 confirm that all investigated samples exhibit a common spectral pattern, particularly the stable minimum at 975 nm, which can be considered a universal spectral marker of combustion residues of lignocellulosic biofuels. The similarity of spectral characteristics between flax-based briquettes and the control wood sample indicates the comparability of their combustion products in terms of chemical composition and supports the possibility of using flax biomass as an alternative energy source without significant changes in the nature of combustion residues. The obtained results are consistent with previous studies [3], [4], which indicate that the properties of solid biofuels are largely determined by the nature of the raw material. At the same time, the present study extends these findings by introducing a spectrophotometric approach for evaluating combustion residues, providing an additional analytical tool for assessing the quality and environmental safety of biofuel materials.

Table 1

Characteristic transmission peaks of combustion residue extracts

Sample	Peak type	Wavelength, nm	Transmission, %	Interpretation
L70/S30	Maximum	540–710	~90–95	Residual organic chromophores
	Maximum	685–815	~92–97	Lignocellulosic structures
	Minimum	975	51.19	O–H absorption
	Maximum	~1070	~95–98	Low absorption
L50/S50	Maximum	540–710	~85–92	Binder influence
	Maximum	700–910	~88–94	Shift due to sapropel
	Minimum	975	45.41	Increased absorption
	Maximum	~1070	~92–96	Reduced absorption
L100	Maximum	540–710	~90–96	Pure biomass
	Maximum	685–815	~92–97	Typical residues
	Minimum	975	51.03	Stable marker
	Maximum	~1070	~95–98	Low absorption
D (wood)	Maximum	540–710	~92–97	Reference material
	Maximum	685–815	~93–98	Wood residues
	Minimum	975	54.63	O–H absorption
	Maximum	~1070	~96–99	Minimal absorption

Conclusions. The conducted study confirmed that solid biofuel briquettes produced from non-conditioned oil flax stems form combustion residues with similar optical properties regardless of binder content. Spectrophotometric analysis of aqueous extracts proved to be an effective and rapid method for evaluating the composition and properties of combustion residues, enabling the identification of characteristic spectral features in the wavelength range of 200–1100 nm. A stable transmission minimum at a wavelength of 975 nm was identified for all investigated samples, including flax-based briquettes and the control wood sample. This feature is attributed to the second overtone of O–H stretching vibrations and can be considered a diagnostic spectral marker. The differences in transmission values between flax-based biofuels and the control wood sample do not exceed 3–4%, indicating a high degree of similarity in the chemical composition of their combustion residues. The use of sapropel as a natural binder (30–50%) does not significantly alter the overall spectral characteristics of combustion products, although it increases absorption intensity due to a higher content of mineral components. The obtained results confirm the feasibility of using oil flax stem biomass as a raw material for solid biofuels with properties comparable to conventional wood-based fuels. The proposed spectrophotometric approach can be applied as a rapid diagnostic tool for comparative evaluation of solid biofuel materials and their environmental safety.

References

1. Demirbaş, A. (2009). Biofuels: Securing the planet's future energy needs. *Energy Conversion and Management*, 50(9), 2239–2249. https://doi.org/10.1016/j.enconman.2009.05.010
2. McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. *Bioresource Technology*, 83(1), 37–46. https://doi.org/10.1016/S0960-8524(01)00118-3
3. Kaliyan, N., & Morey, R. V. (2009). Factors affecting strength and durability of densified biomass products. *Biomass and Bioenergy*, 33(3), 337–359. https://doi.org/10.1016/j.biombioe.2008.08.005

4. Tumuluru, J. S., Wright, C. T., Hess, J. R., & Kenney, K. L. (2011). A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. *Biofuels, Bioproducts and Biorefining*, 5(6), 683–707. https://doi.org/10.1002/bbb.324

5. Obernberger, I., & Thek, G. (2010). *The Pellet Handbook: The Production and Thermal Utilization of Biomass Pellets*. Earthscan. https://www.researchgate.net/publication/237079666_The_Pellet_Handbook_The_Production_and_Thermal_Utilization_of_Pellets

6. Skoog, D. A., Holler, F. J., & Crouch, S. R. (2014). *Principles of Instrumental Analysis* (6th ed.). Cengage Learning.

7. Christian, G. D. (2004). *Analytical Chemistry* (6th ed.). John Wiley & Sons. https://doi.org/10.1002/0471680575

8. Didukh, V., Yaheliuk, S., Artyukh, T., Albota, D., Holiy, O. (2022) Decrease of elastic properties of oleaginous flax residues by decortication. INMATEH - Agricultural Engineering. Vol. 67, No. 2. P. 285–292. https://doi.org/10.35633/inmateh-67-29

9. Yaheliuk, S., Didukh, V., Fomich, M., Yaheliuk, O., Kuzmina, T., Boiko, G. (2025) Optimization of technological parameters for fuel roll production using agricultural crop stem biomass. INMATEH - Agricultural Engineering. Vol. 75. P. 243–252. https://doi.org/10.35633/inmateh-75-21

10. Yaheliuk, S., Didukh, V., Busnyuk, V., Boyko, G., Shubalyi, O. (2020) Optimization on efficient combustion process of small-sized fuel rolls made of oleaginous flax residues. INMATEH - Agricultural Engineering. Vol. 62, No. 3. P. 361–368. https://doi.org/10.35633/inmateh-62-38

11. Yaheliuk, S., Fomych, M., Rechun, O. (2024) Global market trends of grain and industrial crops. Commodity Bulletin. 2024. Vol. 17, No. 1. P. 134–145. https://doi.org/10.62763/ef/1.2024.134

12. National Waste Management Strategy in Ukraine until 2030: approved by the Resolution of the Cabinet of Ministers of Ukraine No. 820-r of 08.11.2017. Official legal portal of the Verkhovna Rada of Ukraine.

13. Poletto, M., Ornaghi, H. L., Zattera, A. J. (2014) Native cellulose: structure, characterization and thermal properties. *Materials*. 7, 6105–6119. https://doi.org/10.3390/ma7096105

14. Faix, O. (2001) Classification of lignins from different botanical origins by FTIR spectroscopy. *Holzforschung*. 1991, 45(S1), 21–27. https://doi.org/10.1515/hfsg.1991.45.s1.21

15. Workman, J., Weyer, L. (2007) *Practical Guide to Interpretive Near-Infrared Spectroscopy*. CRC Press. https://www.researchgate.net/publication/250420699_Practical_Guide_to_Interpretive_Near-Infrared_Spectroscopy_By_Jerry_Workman_Jr_and_Lois_Weyer

16. Clark, R. N. (1999) Spectroscopy of rocks and minerals, and principles of spectroscopy. In: *Manual of Remote Sensing*. https://pubs.usgs.gov/publication/70196852

17. Osborne, B. G., Fearn, T., Hindle, P. H. (1993) *Practical NIR Spectroscopy with Applications in Food and Beverage Analysis*. Longman, https://www.cabidigitallibrary.org/action/doSearch?do=Practical+NIR+spectroscopy+with+applications+in+food+and+beverage+analysis.