ГІДРОТЕХНІЧНЕ БУДІВНИЦТВО, ВОДНА ІНЖЕНЕРІЯ ТА ВОДНІ ТЕХНОЛОГІЇ

HYDRAULIC CONSTRUCTION, WATER ENGINEERING AND WATER TECHNOLOGIES

UDC 628.38; 502.174
DOI https://doi.org/10.32782/tnv-tech.2025.1.52

CHARACTERISTICS OF THE PROPERTIES OF ALTERNATIVE FUEL CREATED FROM MUNICIPAL WASTE

Kravchenko V. I. *– Ph.D in Technical Sciences, Associate Professor, Associate Professor at the Department of Hydraulic Construction, Water and Electrical Engineering, Kherson State Agrarian and Economic University*
ORCID ID: 0000-0002-4989-1591
Scopus-Author ID: 59539938300

The article presents the rationale, method of manufacturing and obtaining composite biofuel in the form of pellets based on municipal waste, as well as methods used to determine its main thermal characteristics. Traditional methods of utilizing sewage sludge, which remains for years in sludge landfills, and fallen leaves are inefficient from an economic and environmental point of view or are prohibited. Given the strict environmental standards and high costs of waste processing in Ukraine, their disposal becomes a critical problem due to mass production and large volumes. Utilization of sludge sediments of municipal wastewater treatment plants with their use as a source of thermal energy is one of the promising areas. Adding fallen leaves to the sediments will allow the production of environmentally safe composite biofuels with improved physical and thermal characteristics. The production of granular fuel was carried out using sewage sludge from municipal wastewater treatment plants of the Dnipro-Kirovograd Industrial Complex and fallen maple leaves of the city of Kropyvnytskyi. The main thermal characteristics of composite pellets were experimentally established, namely: density, strength, moisture and ash content. A mixture of sewage sludge and fallen leaves in proportions from 10/90% to 50/50%, respectively, allows obtaining sufficiently high-calorie pellets with a heat of combustion of 18.0 MJ/kg. The resulting composite pellets are environmentally friendly fuel, are low-cost and have sufficiently high thermal characteristics. The use of such alternative biofuels is appropriate for use not only in residential heating systems, but also in industrial plants for the production of thermal and electrical energy in the agro-industrial, municipal and energy sectors.

Key words: *sewage sludge, fallen leaves, recycling, biofuel pellets, thermal processing*

Кравченко В. І. Характеристика властивостей альтернативного палива, створеного з відходів комунальних підприємств

У статті представлено обґрунтування, спосіб виготовлення і отримання композитного біопалива у вигляді пелет на основі відходів комунальних підприємств, а також методи, що використовуються для визначення його основних теплотехнічних характеристик. Традиційні методи утилізації осадів стічних вод, що залишаються роками на мулових звалищах, та опалого листя малоефективні з економічної та екологічно точки

зору або заборонені. Враховуючи суворі екологічні норми та високі витрати на переробку відходів в Україні, їх утилізація стає критичною проблемою через масове виробництво та великі обсяги. Утилізація мулових осадів комунальних очисних споруд із застосуванням їх як джерела одержання теплової енергії є одним з перспективних напрямків. Додавання до осадів опалого листя дозволить виготовляти екологічно безпечне композитне біопаливо з покращеними фізичними і термічними характеристиками. Виготовлення гранульованого палива було проведено з використанням осаду стічних вод комунальних очисних споруд ОКВП «Дніпро-Кіровоград» та опалого листя клену міста Кропивницький. Експериментальним шляхом встановлені основні теплотехнічні характеристики композитних пелет, а саме: щільність, міцність, вологість та зольність,. Суміш з осадів стічних вод та опалого листя у пропорціях відповідно від 10/90% до 50/50% дозволяє отримати достатньо висококалорійні пелети із теплотою згоряння 18,0 МДж/кг. Отримані композитні пелети є екологічно нешкідливим паливом, відрізняються малою вартістю та мають достатньо високі теплотехнічні характеристиками. Використання такого альтернативного біопаливо є доцільним для застосування не тільки у житлових системах опалення, а і у промислових установках для виробництва теплової і електричної енергії в агропромисловому, комунальному та енергетичному секторах.

Ключові слова: *осади стічних вод, опале листя, утилізація, біопаливні пелети, термічна переробка.*

Introduction. Today, environmental problems in the existing water management systems of settlements in Ukraine are gradually expanding and remain relevant due to the growing volume of waste. The management of sewage sludge (SS), which is a residue formed during the wastewater treatment process at municipal wastewater treatment plants, is one of the most complex problems in the field of wastewater management [1].

Analysis of recent research and publications. The Law of Ukraine "On Water Disposal and Wastewater Treatment" of 12.01.2023 and EU directives have significantly limited the use of sewage sludge in agriculture and have imposed a ban on its storage. Therefore, today it is necessary to find solutions for the safe neutralization and disposal of these materials [1].

Given the limited natural resources and the rising cost of fossil fuels, thermal conversion of SS into energy and alternative fuels is considered one of the most attractive technologies for processing the growing amount of sludge [2,3]. The thermochemical process is able to provide not only a significant reduction in the volume of SS, but also effective destruction of pollutants.

Another unresolved problem of solid municipal waste processing in Ukraine is the utilization of fallen leaves, which can also be used as an energy source. The use of fallen leaves as biomass has a number of advantages. The main ones are renewability, availability and low carbon dioxide emissions during combustion. Thus, in large cities of Ukraine, about 120,000 m3 of fallen leaves are collected annually, which need to be disposed of [4].

Traditional methods of processing fallen leaves are mainly storage, composting, briquetting, and burning [4,5]. However, this biomass in its usual form is difficult to store and transport due to the low bulk density, which requires significant areas for its placement. Currently, natural ravines or specially dug land ditches are used for storage of fallen leaves, which is often a violation of current legislation, as is burning leaves in the open atmosphere [6].

Although fallen leaves contain a large amount of organic matter and after decomposition turn into a nutrient fertilizer, such a process, in particular composting, requires a long period, and the construction of large-scale structures and their maintenance will require significant operating costs.

The calorific value of pressed fallen leaves is estimated at 17.6-17.8 MJ/kg [7], so it can be effective for the production of thermal and electrical energy [2]. However,

the technology of briquetting fallen leaves currently also does not have enough proven technical solutions, and the known methods with the addition of starch [8] or wax [7] as a binder significantly increase the cost of such fuel.

The specified waste of SS and fallen leaves can be characterized by different properties and variability of composition. Therefore, it is advisable to mix them and convert them into the form of a suitable fuel so that they are suitable for the thermal utilization process. In this case, the synergistic effect of the protein contained in SS [9] and lignin of fallen leaves can be a mechanism for the compatible combination and adhesion of these substances.

In the process of granulating or briquetting a mixture of SS and fallen leaves, it is possible to obtain fuel of a given shape, which will not only make it possible to effectively dispose of waste, but also increase the thermal characteristics of the pressed composite biofuel and simplify its transportation and storage operations [9,10].

The aim of the study. To experimentally determine the properties of the manufactured alternative composite biofuel in the form of pellets based on SS and fallen leaves for its thermal utilization in thermal energy production plants.

Presenting main material. In experimental studies on the production of composite granular biofuel, samples of SS provided by the regional municipal production enterprise (OKVP) "Dnipro-Kirovograd" in Kropyvnytskyi were used: raw sludge (SS-1) and excess activated sludge (SS-2). The sediment samples after centrifugation had a humidity of 75-80%, therefore, before producing granular biofuel from them, they were prepared by thermal and mechanical treatment. After treatment, the samples were destroyed with the formation of individual particles, of which the majority (60-70%) had a size of 3-5 mm and a humidity of 16%.

The choice of fallen maple leaves as a component of the composite fuel was due to the fact that one of the most common ornamental trees in the city of Kropyvnytskyi is maple. After its collection, it was crushed and sieved through a laboratory sieve No. 9 with round holes with a diameter of 9 mm.

In experimental studies of the production of biofuel samples from a mixture of SS and fallen maple leaves, the following technological sequence was used: collection of fallen leaves, separation of foreign objects from them; drying of SS and fallen leaves and their crushing; preparation of a mixture of components; pressing into a closed matrix; study of the surface of the pellets; determination of the heat of combustion and ash content of the produced pellets.

To produce pellets from a mixture of SS and fallen maple leaves in a closed matrix, a universal testing machine УВМ-50 and a press device with a mold and a punch $d = 16$ mm were used, the general appearance of which, as well as the process of manufacturing biofuel samples, are given in [1].

Fractographic study of the surface structure of biofuel granules made from SS and fallen maple leaves was carried out using an optical-digital unit consisting of a stereoscopic microscope model МВС-9, a Web camera and a computer. The general appearance of the optical-digital unit for fractographic studies is shown in Figure 1.

The ash content was assessed using a muffle furnace. The crucible with the installed sample was placed in a muffle furnace and ashed with subsequent holding in it at a temperature of 800 °C for 1-1.5 hours (until the carbon was completely burned out) [11].

During the study, the main thermal characteristics of composite pellets were determined: density, calorific value and ash content. The results of experimental studies are given in Table 1.

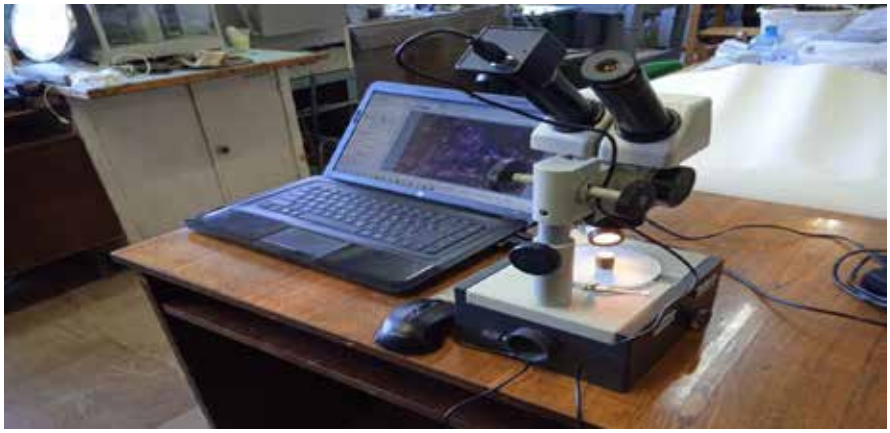

Fig. 1. Optical-digital unit for fractographic studies

Table 1

Main results of experimental studies

№№	Raw	% of raw material in the mixture	Pellet density ρ_p, g/cm^3		Heat of combustion Q^c, MJ/kg,	Ash content, %
			Pressure 130.5 MPa	Pressure 217.5 MPa		
81	Maple leaves	90	1,04	1,09	16,7	15,7
	SS-1	10				
92	Maple leaves	70	1,09	1,15	17,3	22,1
	SS-1	30				
13	Maple leaves	50	1,17	1,23	18,0	29,2
	SS-1	50				
14	Maple leaves	90	1,05	1,08		
	SS-2	10				
15	Maple leaves	70	1,09	1,18		
	SS-2	30				
16	Maple leaves	50	1,15	1,29		
	SS-2	50				

The general appearance of pellets made from a mixture of OSW and fallen maple leaves is shown in Figure 2.

When producing composite fuel from a mixture of raw sediment and excess sludge (SS-1 and SS-2) with fallen leaves with a humidity of ≈ 15% in different proportions at final pressures of 130.5…217.5 MPa, pellet samples with a sufficiently smooth surface were formed (Fig. 2), which had a density ρ_p of more than 1.0 g/cm3 (Table 1) and met European standards [12].

The nature of the structure of the surface of the pellets and the density of the gaps between the particles of the raw material after pressing were studied on samples of different densities using a microscope and an eyepiece with a scale. A photo of the surface structure of composite pellet samples is presented in Figure 3.

a *b* *c* *d*

Fig. 2. General view of pellet samples (diameter 16 mm) made from a mixture of OSW and maple leaves, the content of which is respectively: a, b (30/70%); c, d (50/50%); a, c – pressure 130.5 MPa; b, d – pressure 217.5 MPa

a *b* *c*

Fig. 3. Photo of the surface structure of composite pellet samples and c – general view of their ash residue after combustion: a – outer surface of a sample made of SS and fallen maple leaves with a final pressure of 130.5 MPa; b – the same with a final pressure of 217.5 MPa

The results of fractographic studies showed that with increasing pellet density (at final pressures of 130.5 and 217.5 MPa), the distance between particles on the surface decreases from 0.075 mm (Fig. 3a) to 0.02 mm (Fig. 3b). The sufficiently high density and strength of the manufactured pellet samples is due to the protein content in the SS and lignin in the leaf, and increasing pressure contributes to a decrease in the number of existing boundaries between particles.

The general appearance of the ash residue after combustion of composite pellets with raw sediment (SS-1) and leaves is shown in Figure 3c, and its values are given in Table 1. The ash content of fuel samples was determined experimentally after their combustion with subsequent conversion to dry mass. The ash content of composite pellets increases with an increase in the sediment content in them. Thus, when the concentrations of fallen maple leaves and SS-1 change from 90/10% to 50/50%, the ash content increases from 15.7% to 29.2% (Table 1). The ash residues after combustion of the samples (at a temperature ≤ 800 °C) had a brittle structure and were easily destroyed with minor efforts with a transition to a heterodisperse state (Fig. 3c).

The higher calorific value Q^c of the studied pellets, which is given in Table 1, was determined by the calculation method taking into account the obtained experimental data on ash content. To determine the higher calorific value, the equation of D. Mendeleev was used [13].

The results given in Table 1 show that the value of $Q_ç$ of pellets made from SS-1 and maple leaves increases with an increase in the sediment content from 16.7 to 18.0 MJ/kg.

Conclusions. Using pre-mixing of prepared sewage sludge from municipal treatment plants and fallen leaves from settlements, samples of alternative biofuel were produced in the form of composite pellets.

As a result of experimental studies, it was determined that from the prepared mixture of SS and fallen maple leaves, when compressed to final pressures of 130.5…217.5 MPa in a press device, pellet samples with a high-quality texture and density of 1040-1290 kg/m3 are formed, which meets the requirements of European standards $\rho \geq 1.0$ g/cm3.

The determined ash content of the manufactured pellet samples was 15.7-29.2%, and the calculated heat of combustion per dry mass was 16.7-18.0 MJ/kg, which is comparable to the heat of combustion of briquettes from wood waste, brown coal, peat.

The creation of a composite fuel from sewage sludge and fallen leaves will contribute to solving the problem of municipal waste disposal and increasing the production of renewable energy. The use of such biofuel is cost-effective, has environmental benefits and will be effective for use not only in small-scale residential heating systems, but also in industrial installations for the production of thermal energy in the agro-industrial, municipal and energy sectors.

BIBLIOGRAPHY:

1. Кравченко В. І. Виготовлення та експериментальна оцінка біопалива на основі осадів стічних вод для одержання теплової енергії та будівельного матеріалу [Електронний ресурс] / В. І. Кравченко // Вісник ХНТУ. Видавничий дім «Гельветика». 2024. 2 (89). С. 32-37. Режим доступу: https://doi.org/10.35546/kntu2078-4481.2024.2.4

2. Бабаєв В.М., Панов В.В., Хайло Я.М., Волков В.М., Горох М.П. Альтернативні технологічні рішення проблеми повної утилізації мулового осаду стічних вод/ В.М. Бабаєв, В.В. Панов, Я.М. Хайло, В.М. Волков, М.П. Горох // Комунальне господарство міст. 2018. № 144. С. 32-42.

3. Syed Shatir A. Syed- Hassan, Yi Wang, Song Hu, Sheng Su, Jun Xiang. Thermochemical processing of sewage sludge to energy and fuel: Fundamentals, challenges and considerations. https://www.sciencedirect.com/science/article/abs/pii/S1364032117309036

4. Д'яконов В.І., Бузіна І.М., Хайнус Д.Д. Екологічні методи утилізації опалого листя та рослинних відходів [Електронний ресурс] / В.І. Д'яконов, І.М. Бузіна, Д.Д. Хайнус// Таврійський науковий вісник. 2020, № 111. С. 258-264. Режим доступу: http://www.tnv-agro.ksauniv.ks.ua/archives/111_2020/37.pdf

5. Piakovych & Dzurenda (2015) Kharakterystyky horinnia opaloho lystia dekoratyvnykh derev u miskykh ta lisoparkovykh zonakh [Burning characteristics of fallen leaves of ornamental trees in urban and forest park areas] *Zhurnal "Bioresursy",* vol. 10(3). Available at: doi: 10.15376/biores.10.3.5563-5572

6. Закон України «Про схвалення Національної стратегії управління відходами в Україні до 2030 року». [Електронний ресурс]. Режим доступу: https://zakon.rada.gov.ua/laws/show/820-2017-%D1%80#Text

7. Сайт: Пелети і брикети з опалого листя? [Електронний ресурс]. Режим доступу: https://bio.ukr.bio/ua/articles/10832/

8. Використання опалого листя у виробництві паливних брикетів. [Електронний ресурс]. Режим доступу: https://repository.kpi.kharkov.ua/items/f092ad7f-0a31-4eb6-9086-706c7ce8223f

9. Кравченко В.І., Білоус Ю.В., Кравченко В.П. Створення та обгрунтування композитного палива на основі осаду стічних вод [Електронний ресурс] / В.І. Кравченко, Ю.В. Білоус, В.П. Кравченко //Технічні науки. Херсон: ХДАЕУ. 2023. 3. С. 88-94. Режим доступу: http://journals.ksauniv.ks.ua/index.php/tech/article/view/403

10. Longbo Jiang, Jie Liang, Xingzhong Yuan, Hui Li, Changzhu Li, Zhihua Xiao, Huajun Huang, Hou Wang, Guangming Zeng. Co-pelletization of sewage sludge and biomass: The density and hardness of pellet. https://www.sciencedirect.com/science/article/abs/pii/S0960852414007433?via%3Dihub

11. Сайт: Європейські стандарти на якість пелет. [Електронний ресурс]. Режим доступу: https://bio.ukr.bio/ua/articles/9243/

12. Ялечко В.І. Підвищення ефективності енерготехнологічного процесу спалювання здрібненої деревної біомаси: дис….кандата техн. наук: спец. 05.14.06 «Технічна теплофізика та промислова теплоенергетика»/ В.І. Ялечко. Львів: Національний університет «Львівська політехніка». 2021. 149 с.

REFERENCES:

1. Kravchenko V. I. (2024) Vyhotovlennia ta eksperymentalna otsinka biopalyva na osnovi osadiv stichnykh vod dlia oderzhannia teplovoi enerhii ta budivelnoho materialu [Production and experimental evaluation of biofuel based on sewage sludge for obtaining thermal energy and building material]. *Visnyk KhNTU. Vydavnychyi dim «Helvetyka» – KhNTU Bulletin. Helvetica Publishing House.* Retrieved from https://doi.org/10.35546/kntu2078-4481.2024.2.4 [in Ukrainian].

2. Babaiev V.M., Panov V.V., Khailo Ya.M., Volkov V.M., & Horokh M.P. (2018) Alternatyvni tekhnolohichni rishennia problemy povnoi utylizatsii mulovoho osadu stichnykh vod [Alternative technological solutions to the problem of complete disposal of sewage sludge]. *Komunalne hospodarstvo mist – Communal management of cities*,144, 32-42 [in Ukrainian].

3. Syed Shatir A. Syed- Hassan, Yi Wang, Song Hu, Sheng Su, Jun Xiang. Thermochemical processing of sewage sludge to energy and fuel: Fundamentals, challenges and considerations. https://www.sciencedirect.com/science/article/abs/pii/S1364032117309036

4. Diakonov V.I., Buzina I.M., Khainus D.D. (2020) Ekolohichni metody utylizatsii opaloho lystia ta roslynnykh vidkhodiv [Ecological methods of disposal of fallen leaves and plant waste]. *Tavriiskyi naukovyi visnyk – Taurian Scientific Bulletin,* 111, 258-264. Retrieved from http://www.tnv-agro.ksauniv.ks.ua/archives/111_2020/37.pdf [in Ukrainian].

5. Piakovych & Dzurenda (2015) Kharakterystyky horinnia opaloho lystia dekoratyvnykh derev u miskykh ta lisoparkovykh zonakh [Burning characteristics of fallen leaves of ornamental trees in urban and forest park areas] *Zhurnal "Bioresursy",* vol. 10(3). Available at: doi: 10.15376/biores.10.3.5563-5572

6. Zakon Ukrainy «Pro skhvalennia Natsionalnoi stratehii upravlinnia vidkhodamy v Ukraini do 2030 roku» ["On the approval of the National Waste Management Strategy in Ukraine until 2030"]. (n.d.). zakon.rada.gov.ua. Retrieved from https://zakon.rada.gov.ua/laws/show/820-2017-%D1%80#Text [in Ukrainian].

7. Sait: Pelety i brykety z opaloho lystia? [Site VIP company of the day: Pellets and briquettes from fallen leaves?] Retrieved from https://bio.ukr.bio/ua/articles/10832/ [in Ukrainian].

8. Vykorystannia opaloho lystia u vyrobnytstvi palyvnykh bryketiv [The use of fallen leaves in the production of fuel briquettes] Retrieved from https://repository.kpi.kharkov.ua/items/f092ad7f-0a31-4eb6-9086-706c7ce8223f [in Ukrainian].

9. Kravchenko V.I., Bilous Yu.V., Kravchenko V.P. (2023) Stvorennia ta obhruntuvannia kompozytnoho palyva na osnovi osadu stichnykh vod [Creation and substantiation of composite fuel based on sewage sludge]. *Tekhnichni nauky. Kherson: KhDAEU- Technical sciences. Kherson: KhSAEU, 4,* 88-94. Retrieved from http://journals.ksauniv.ks.ua/index.php/tech/article/view/403 [in Ukrainian].

10. Longbo Jiang, Jie Liang, Xingzhong Yuan, Hui Li, Changzhu Li, Zhihua Xia o, Huajun Huang, Hou Wang, Guangming Zeng (2021) Co-pelletization of sewage sludge and biomass: The density and hardness of pellet. https://www.sciencedirect.com/science/article/abs/pii/S0960852414007433?via%3Dihub

11. Sait: Yevropeiski standarty na yakist pelet [Site: European standards for the quality of pellets] Retrieved from https://bio.ukr.bio/ua/articles/9243/ [in Ukrainian].

12. Yalechko V.I. (2021) Pidvyshchennia efektyvnosti enerhotekhnolohichnoho protsesu spaliuvannia zdribnenoi derevnoi biomasy [Increasing the efficiency of the energy-technological process of burning chopped wood biomass]. Candidate's thesis. Lviv: Lvivska politekhnika [in Ukrainian].