OPTIMIZATION ON EFFICIENT COMBUSTION PROCESS OF SMALL-SIZED FUEL ROLLS MADE OF OLEAGINOUS FLAX RESIDUES
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ОПТИМІЗАЦІЯ ЕФЕКТИВНОГО ПРОЦЕСУ ГОРІННЯ МАЛОГАБАРИТНИХ ПАЛИВНИХ РУЛОНІВ ІЗ ЗАЛИШКІВ ПІСЛЯ ЗБИРАННЯ ЛЬОНУ ОЛІЙНОГО

Svitlana Yaheliuk[1], Volodymyr Didukh[2], Vitally Busnyuk[2], Galina Boyko[3] Oleksandr Shubalyi[4]
[1] Lutsk National Technical University, Department of Commodity Research and Expertise Customs, Lutsk, Ukraine;
[2] Lutsk National Technical University, Department of agricultural engineering, Lutsk, Ukraine;
[3] Kherson National Technical University, Department of Commodity Studies, Standardization and Certification / Kherson, Ukraine;
[4] Lutsk National Technical University, Department of Economics, Lutsk, Ukraine
Tel: +380955371898; E-mail: s.yagelyuk@lntu.edu.ua
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ABSTRACT
Currently, the use of secondary agricultural raw material is a topical issue. There are various applications of agricultural crop residues possible, but they are finance- and energy-consuming. Burning crop residues is very harmful for the environment. One of the ways to solve the problem is the production of solid biofuel that can be used to heat buildings. The authors suggest producing solid biofuel in the form of small-sized fuel rolls / pellets (SFR), which are made of oleaginous flax residues. As a result of the conducted experimental investigations, the authors have proved the efficiency and the environmental safety of SFR consumption. The new fuel can be recommended if the requirement of efficient and ecologically safe combustion is met. Thus, the influence of small-sized fuel rolls' properties on the process of their combustion as well as quantitative and qualitative analysis of the combustion gases from burning solid fuel made of oleaginous flax residues have been investigated. The paper presents the results proving that SFR combustion is the most efficient on condition of providing reduced moisture (10-12%) and reasonable density (80 kg/m^3) in the process of pellet production. In addition, it has been determined that there is a significant reduction of harmful CO emissions and normalization of CO_2 concentration. The application of the suggested solid biofuel can make it possible to solve the problem of using oleaginous flax residues and provide cheap fuel for household purposes.

РЕЗЮМЕ
На сьогодні актуальне використання вторинної сільськогосподарської сировини. Є різні можливості застосування рослинних сільськогосподарських відходів, проте вони фінансово- та енерговитратні. Спалювання залишків сільськогосподарських культур шкодить навколишньому середовищу. Шляхом вирішення проблеми є виготовлення твердого біопалива для опалення будівель. Автори пропонують використовувати у якості твердого біопалива малогабаритні паливні рулони (МПР), які виготовляють із відходів, що залишаються після збирання олійного льону. В результаті проведених експериментальних досліджень, автори встановили ефективність та високу екологічну безпечність спалювання МПР. Нове паливо може бути рекомендованим, якщо воно задовольняє умову ефективного та екологічного горіння. Тому дослідження впливу властивостей малогабаритних паливних рулонів на час їх ефективного горіння та кількісний й якісний аналіз димових газів від згоряння твердого палива з відходів збирання олійного льону є актуальним. В статті наведені результати які доводять, що найбільшої ефективності горіння (МПР) можна досягти зниженням вологості та дотриманням раціональної щільності під час виробництва. Також виявлено, що спалювання характеризується суттєвим зниження шкідливих викидів CO, зниженням концентрації CO_2, приведеної до нормальних умов. Використання запропонованого нового твердого біопалива дозволить вирішити задачу використання залишків рослинної сільськогосподарської сировини олійного льону та забезпечить населення дешевим видом палива.

INTRODUCTION

A large amount of plant residues remain in the field after crops harvesting. By now, the farmers have not found many ways to utilize these residues. Burning them is the fastest and easiest way to dispose of plant agricultural waste. This is a standard practice for different countries around the world. As a result of agricultural residues burning, there can be two problems: air pollution and damage to fertile soils. At the same time, there is a steady increase in the cost and reduction of existing energy resources. Therefore, more and more attention is paid to modern, "green" technologies.

The burning of plant agricultural waste is also an urgent problem for Ukraine. During the harvesting done by the oleaginous flax harvester, windrows of the stem fibre mass, that are of a considerable size, remain on the field. That is why conversion of oleaginous flax stem fibre mass to solid biofuel is a good opportunity to overcome the energy crisis in Ukraine. Production of such fuel from oleaginous flax residues will improve environmental safety and does not require large financial costs. As a result of research this type of fuel was produced (*Yaheliuk S. et al., 2019*). Solid biofuel obtained from oleaginous flax residues is in the form of dense small-sized fuel rolls of a small diameter, which can be used for heating buildings during the cold season. They are suitable for all boilers that are designed to use solid fuel.

Most boilers normally produce carbon monoxide as a part of their operation. Such emissions must comply with the European Commission's ambient air quality requirements (*Air Quality Standards, 2019*) and international requirements for boilers (*Technical Safety BC, 2018*).

In order to use a new type of solid biofuel effectively, it is necessary to experimentally study the performance characteristics, namely the effective combustion time, as well as the environmental safety of smoke gas emissions produced by the combustion of this biofuel. This type of studies have not been conducted before and this article is dedicated to them.

Conservation of energy and the environment, the search for new environmental types of fuel are the important challenges of our time. At the same time, the production of plant raw materials is a significant factor in environmental pollution. After all, combustion remains the main mean of plant residues disposal. Nowadays a lot of attention is paid to air pollution throughout the world. The World Health Organization has highlighted the damage that air pollution causes to humankind (*WHO, 2018*). The Fact Sheet of the Commission for Environmental Cooperation stated that combustion emission of agricultural raw materials contained an unacceptable amount of dioxins. Prospects for reduction of flue gas from agricultural waste are to be analysed (*CEC, 2014*).

A majority of EU Member States have implemented the ban of open air burning of agricultural plant waste according to *Amann M.*, (2017). Especially hazardous is air pollution with carbon monoxide, carbon dioxide and other chemicals emitted by the combustion processes (*Gaba A., Iordache S.F., 2011*). The effects of agricultural waste incineration related to soil, air, water and health were examined by *Kumar P., (2015)*. There are many studies on the potential uses of plant agricultural waste. The manufacture of fuel briquettes from various plant wastes was proposed except for oleaginous flax (*Gregory M., 2016*).

Oleaginous flax is an important industrial culture. It has a worldwide distribution and it is rapidly developing in Ukraine (*Yaheliuk S. et al., 2018*). However, there is a problem of processing stem fibre mass (SFM) after collecting seeds. The definition of problems and directions of use can be found in *Berglund D.R. (2002).*

The use of flax waste as a component of composite materials was suggested by *Baley C., et al. (2019)*. There are also attempts to use the oleaginous flax waste collection to manufacture fibre. The results of a study of the possibility of fibre extraction from oleaginous flax were obtained by *Ouagne P. et al., (2017).* The studies of oleaginous flax fibres were conducted thorough out by *Tuluchenko N.et al., (2016)*. An innovative technology to obtain such fibre was proposed by *Chursina L., (2019)*. There have been attempts to use oleaginous flax for the production of biodiesel *(Dixit S. et al., 2012*). However, all scientists note the high-energy consumption of such production and the need for significant financial costs.

The production of solid biofuel from oleaginous flax does not require significant financial costs and can provide the solutions to many problems. Until now, this kind of production was not possible, since modern means of forming rolls from agricultural materials were solely able to produce the rolls of a huge diameter up to 3.5 m *(Gummert M. et al., (2020)*. This makes them impossible to be used as a fuel for modern boilers, since the dimensions of boilers fuel holes are limited in diameter (up to 0.9 m).

The authors proposed a technology and equipment for manufacturing small–sized fuel rolls (SFR) as a solid fuel from oleaginous flax waste (*Didukh V. et al., 2019*).

However, the dependency of the effective time of the small–sized fuel rolls combustion on their technological parameters has not been determined. There is also no assessment on such fuel combustion environmental safety. Smoke gases in the solid fuel boilers chimneys during the combustion of oleaginous flax waste SFR have not been analysed. The authors consider the raised questions in this article.

MATERIALS AND METHODS

The research was conducted to justify the feasibility of producing a new type of biofuel - SFR based on the study of its effective combustion time and the quantitative and qualitative composition of smoke gases from combustion in solid fuel boilers.

The factors that influence the efficient combustion of solid biofuel are the geometric dimensions (diameter X_1), the humidity (X_2), and the density of the material (X_3). Therefore, the small-sized fuel rolls made of oleaginous flax residues, with a diameter of 300, 400, 500 (mm) were produced for the research; the roll density was 80, 95, 110 (kg/m^3); the SFR humidity was changed by 10, 15, 20 (%). The experimental combustion was performed in the KALVIS 400 boiler (Lithuania).

The experimental study of the effective time of combustion was conducted by the method of experiment mathematical planning. We used a symmetric non-positional Box-Behnken Experimental Design (*Aslan N., Cebeci Y., 2007*). In order to implement a three-factor experiment up to this plan, it is necessary to conduct 15 experiments.

For the purpose of compiling the factors and levels of variation table (Table 1) we took into account the previous studies' results and information available from written sources. The Box-Behnken plan is designed to use three levels for each factor: upper (+1), main (0), and lower (-1).

Table 1

Variables and their levels in Box-Behnken design

Levels of variation	X_1 - Roll diameter D, mm	X_2 - Material humidity W, %	X_3 - Roll density ρ, kg/m^3
Upper (+1)	500	20	110
Main (0)	400	15	95
Lower (-1)	300	10	80
Range of variation	100	5	15

The experiment planning matrix is presented in Table 2 in a coded form. The order of experiments was established using a table of random numbers. The response function (effective burning time) in the area of factor, space is presented as a nonlinear regression equation (1):

$$Y_i = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 \quad (1)$$

The obtained data were processed using the developed program in the Mathcad environment.
During the experiments, both the qualitative and quantitative composition of smoke gas emission produced by the combustion of each variant of oleaginous flax waste SFR were controlled.

A portable gas analyser Testo 350 was used for the analysis of smoke gases from the combustion of oleaginous flax waste SFR (*www.testo350.com*). It has everything required to study the parameters of the combustion process of oleaginous flax waste SFR.

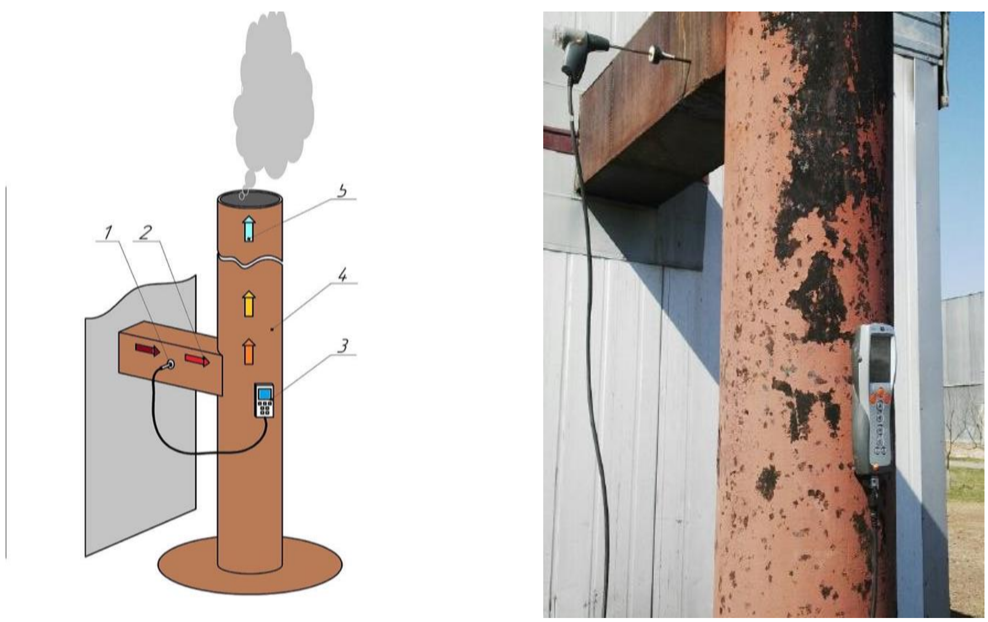
The device can be used in the adverse environmental conditions. The Testo 350 gas analyser consists of three separate parts: a control unit, an analyser unit and measuring probes. The main parameters of Testo 350 include the oxygen O_2, carbon monoxide CO and nitrogen oxides NO_x volume fractions measurements. The qualitative and quantitative composition of the oleaginous flax SFR combustion products' residues were measured using a portable Testo 350 gas analyser (Fig. 1).

Table 2

Design of experiment

Experiment number	Roll diameter D, mm	Material humidity W, %	Roll density ρ, kg/m^3
1	500	20	95
2	300	20	95
3	500	10	95
4	300	10	95
5	500	15	110
6	300	15	110
7	400	15	80
8	400	15	80
9	400	20	110
10	400	10	110
11	400	20	80
12	400	10	80
13	400	15	95
14	400	15	95
15	400	15	95

The oxygen O_2, carbon monoxide CO and nitrogen oxides NO_x volume fractions in smoke gases were measured. These parameters of the gas-air environment make it possible to determine rational modes of fuel combustion with a maximum coefficient of performance (COP) and with minimal emission of harmful gases into the atmosphere. Smoke gases from the combustion of oleaginous flax SFR samples were studied. An ordinary firewood was burned and smoke gases were studied as well. A KALVIS-400 boiler was used for the purpose of research. It is an industrial solid fuel boiler with manual fuel loading.



a b

Fig. 1 - A study of the qualitative and quantitative composition of the smoke gases obtained from the combustion of oleaginous flax SFR waste

a) The scheme of analysis of smoke gases produced by conventional wood combustion: 1. Sensor probe of gas analyser Testo 350, 2. The chimney of the boiler, 3. Gas analyser Testo 350, 4. Tube, 5. The motion of smoke gases; b) picture of the study process

The investigation was carried out in the following order. Firstly, the sensors were put into thermal mode, and the presence of an indication of the volume fraction of oxygen O_2 and carbon monoxide CO was checked. Secondly, the installation of zero value for the carbon monoxide CO sensor was controlled. In order to make it, the hose to supply the mixture from the gas duct was disconnected from the CO sensor. Lastly, the gas analyser was ready to take measurements after monitoring the condition of the oxygen O_2 and carbon monoxide CO channels.

RESULTS AND DISCUSSION

The experiment conducted according to the Box-Behnken design allows to obtain a mathematical model in the form of a regression equation that allows us to set the effective combustion time of SFR based on its technological characteristics: diameter, humidity and density. An analysis of the regression equation makes it possible to evaluate the performance characteristics of the new type of solid biofuel.

Processing data from the results of a three-factor experiment using a three-level second-order plan and using a program created in Mathcad - 2015 allowed us to obtain the regression equation for the effective combustion time of SFR from flex stem fibre mass at different values of its technological characteristics (2).

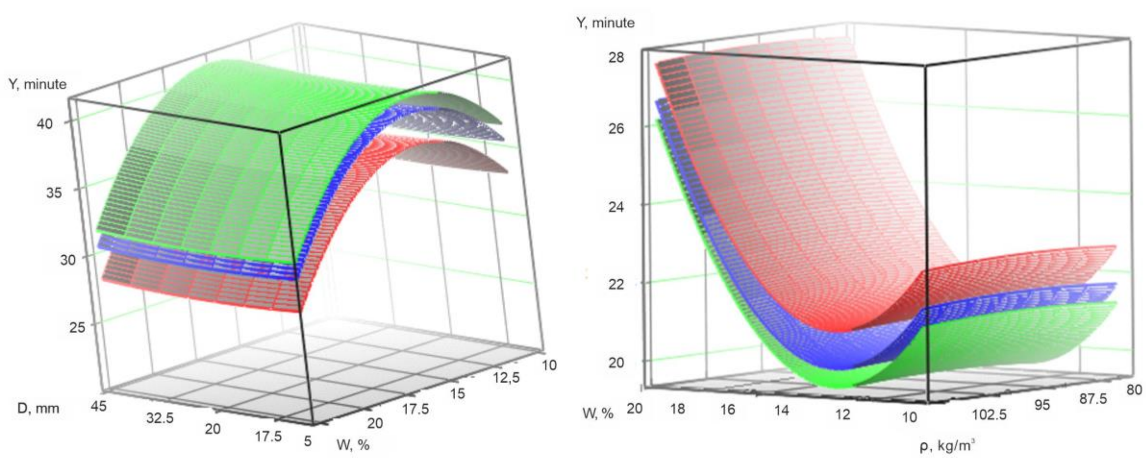
The adequacy of the received regression equation was checked using the F - Fischer criterion according to (*Aslan N., Cebeci Y., 2007*). The calculated value of the Fisher criterion is F_{count} =6.642 with the variance of inadequacy S^2 =3.417 and the variance of reproducibility S_y^2=0.514. The tabular value of the Fisher criterion at the accepted 5% significance level and degrees of freedom f_1=2, f_2=9 was F_{table} = 19.4. Since F_{count} = 6.642, F_{table} = 19.4 the resulting model is adequate.

Finally, the regression equation for the effective combustion time of flex stem fibre mass SFR due to different values of its technological characteristics with natural factors was (2):

$$Y\,(D,W,\rho) = 76.90 + 0.10\,\rho + 1.98\,W + 0.24\,D + 0.001\,\rho^2 + 0.07\,W^2 + 0.0003\,D^2 \qquad (2)$$

where: D – roll diameter, mm; W – material humidity, %; ρ – roll density, kg/m^3

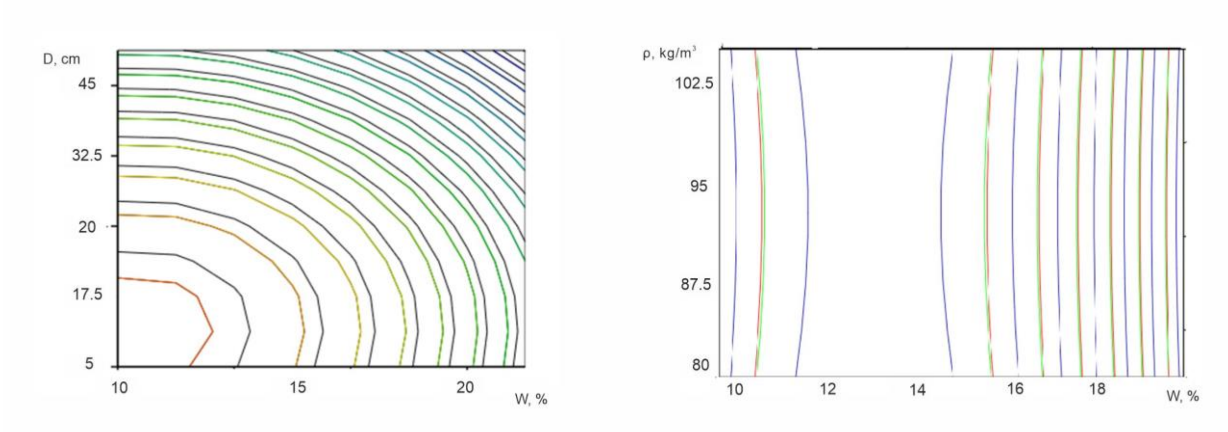
The response surfaces (Fig. 2) and their contour plots (Fig. 3) are constructed using the regression equation (2).



a) *b)*

Fig. 2 - The surface response characterizing the effective combustion of SFR, taking into account:
a) the diameter of the SFR and humidity of the SFM from oleaginous flax waste; b) the density of SFR and humidity of the SFM

As can be seen from the graphs, the optimal effective combustion time of the rolls (25-35 minutes) will be provided if the humidity of the flax stem fibre mass (SFM) from oleaginous flax is within 10-12%. In Fig. 2, it is shown that the SFR diameter does not significantly affect the effective combustion time. However, it is limited by the technological characteristics of the heating boiler. In turn, according to Fig. 3, the rational value of the SFR density is within 80 kg/m^3. Ensuring rational SFR parameters depends on the quality of the manufacturing process and the quality of the oleaginous flax harvesting.



a) b)

Fig. 3 - The contour plot of the response surfaces

a) diameter of SFR and humidity of flax stem fibre mass (SFM) from oleaginous flax;
b) density of SFR and humidity of flax stem fibre mass (SFM) from oleaginous flax

An analysis of the surfaces in Fig. 2a shows that the diameter of the SFR does not affect the effective burning time. Therefore, according to *Yaheliuk S et al, (2019),* the SFR diameter of 40-45 cm can be recommended. One of the important indicators for evaluating the quality of SFR from oleaginous flax waste is the quantitative and qualitative analysis of flue gases from combustion. The research was carried out in the boiler room of the sports complex of the Lutsk National Technical University. The boiler room is equipped with a typical KALVIS-400 hot water boiler. It is adapted for the combustion of firewood, wood waste, briquettes, coal, etc. For comparison, the combustion was carried out and the flue gases of the combustion of conventional firewood were studied. The results of the study of flue gases from the combustion of SFR from oleaginous flax waste and conventional firewood are presented in Table 3.

Parameters of flue gases from the combustion of SFR from oleaginous flax waste and firewood **Table 3**

Parameter Description	Unit	Regular Firewood	SFR from oleaginous flax waste
Boiler heat output	Gcal/h	0.341	0.447
Flue gas temperature in the stack mouth	°C	111.1	112.6
Concentration in the flue gas:			
CO_2	%	4.27	6.6
O_2	%	16.6	14.2
CO	ppm	3822	92
NOx	ppm	25	38
Excess air ratio		4.75	3.07
Heat loss:			
– with flue gases	%	16.01	11.00
– with chemical undersupply	%	5.003	0.085
– to the environment	%	0.55	0.48
Boiler COP	%	78.44	88.44
Fuel consumption	kg/h	120	120
Specific fuel consumption per 1 Gcal of heat produced:	kg/Gcal	182.12	161.52
Saving specific fuel equivalent	kg/Gcal		20.60
Number of boiler hours	h.	4380	4380
Annual equivalent fuel savings	tons/year.		40.31
NO_x concentration reduced to normal conditions and O_2=3%	mg/m³	209.46	205.84
CO concentration reduced to normal conditions and O_2=3%	mg/m³	19590.91	304.89
Annual fuel economy	m³/year		34.367

According to the data obtained, it was found that SFR from oleaginous flax waste during combustion in solid fuel boilers of the KALVIS-400 type give a heating capacity (boiler capacity) higher 0.1 Gcal/hour than in the case of firewood. The experiments showed that the SFR from oleaginous flax waste is characterized by a significant decrease in the content of carbon monoxide CO (up to 92 ppm). The CO content for firewood is 3822 ppm. A significant decrease in the concentration of CO_2 was established, reduced to normal conditions and O2 = 3%. This means that less soot will form on the walls of the boiler, which in turn increases the efficiency and reduces labour costs for cleaning the boiler. It is also a reduction in heat loss from 21.69% for firewood to 11.56 %for SFR from oleaginous flax waste. However, there is a slight increase in nitrogen oxides NO_x in the SFR from oleaginous flax waste. The results of the study showed that the flue gases from the combustion of SFR from oleaginous flax waste comply with the environmental standards.

CONCLUSIONS

Studies have shown the prospects of using small-sized fuel rolls. After all, their production and use as a new type of solid biofuel makes it possible to solve several important tasks at once: processing stem fibre mass that remains in the field after harvesting oleaginous flax, providing the population with fuel to heat buildings, and obtaining new innovative products from ecological plant raw materials.

A regression equation (mathematical model) can assist to determine the effective combustion time of SFR. The model takes into account the technological parameters of small fuel rolls: diameter, density, humidity.

The analysis of the response surfaces and their contour plots shows that SFR humidity is the parameter that affects the most the combustion time. Considering the conditions for manufacturing and storage of this type of fuel, it is recommended to keep the humidity within 10-12% to achieve maximum efficiency.

The rational density of the roll is considered to be 80 kg/m^3. The reduction of harmful emission of carbon monoxide CO and the concentration of carbon dioxide CO_2 has been established. It has been proved that SFR obtained from oleaginous flax waste is characterized by an increase in heating capacity of the boiler by 0.1 Gcal/h and a reduction of harmful CO emission of up to 92 ppm compared to firewood (3822 ppm).

The paper proves the sufficiency and environmental safety of using SFR made of oleaginous flax waste. In the future, the authors would recommend to develop technical regulations for small fuel rolls. This would allow producers to efficiently produce and consumers to use this type of solid biofuel.

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