OPTIMIZATION OF TECHNOLOGICAL PARAMETERS FOR FUEL ROLL PRODUCTION USING AGRICULTURAL CROP STEM BIOMASS / *ОПТИМІЗАЦІЯ ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ ДЛЯ ВИРОБНИЦТВА ПАЛИВНИХ РУЛОНІВ З ВИКОРИСТАННЯМ СТЕЛБОВОЇ БІОМАСИ СІЛЬСЬКОГОСПОДАРСЬКИХ КУЛЬТУР*

Svitlana YAHELIUK*[1)], Volodymyr DIDUKH[1)], Mikhalo FOMICH[1)], Olexandr YAHELIUK[2)]
Tetyana KUZMINA[2)], Galina BOIKO[2)]
[1)] Lutsk National Technical University, Ukraine;
[2)] Kherson National Technical University, Ukraine
**Corresponding author's E-mail: cler2010@gmai.com*
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ABSTRACT
The paper develops a regression model to predict the density of Fuel Rolls produced from Agricultural Crop Stem Biomass. The study evaluates the influence of Variable-volume Pressing Chamber pressure (P, MPa), biomass volume per linear meter (V, m³), and flax stem content (m, %) on Fuel Roll density (ρ). The goal is to optimize these parameters to ensure the desired density of Fuel Roll. A regression analysis combined with response surface methodology was employed. The optimal parameters for Fuel Rolls production include Variable-volume Pressing Chamber pressure of 0.45–0.55 MPa, biomass volumes of 0.65–0.75 m³/m and flax stem content 75%. These technological parameters enable the production of fuel rolls with required density of 110-130 kg/m³. The results show that increasing pressure in the Variable-volume Pressing Chamber enhances Fuel Roll density, while larger biomass volumes lead to lower densities. Additionally, higher flax stem content improves cohesion and compaction, resulting in higher densities. These findings emphasize the importance of fine-tuning technological parameters to optimize Fuel Roll production. Utilizing agricultural crop stems for biofuel production offers significant environmental benefits, including reduced agricultural waste and lower combustion emissions.

РЕЗЮМЕ
У статті розроблено регресійну модель для прогнозування щільності паливних рулонів, вироблених із біомаси стебла сільськогосподарських культур. Дослідження оцінює вплив тиску камери пресування змінного об'єму (P, МПа), об'єму біомаси на погонний метр (V, м³) і вмісту стебла льону (m, %) на щільність рулону палива (ρ). Мета полягає в тому, щоб оптимізувати ці параметри для забезпечення бажаної щільності паливного рулону. Було використано регресійний аналіз у поєднанні з методологією поверхні відгуку. Оптимальними параметрами для виробництва паливних рулонів є тиск у камері пресування змінного об'єму 0,45–0,55 МПа, об'єм біомаси 0,65–0,75 м³/м і вміст стебла льону 75%. Ці технологічні параметри дозволяють виготовляти паливні рулони необхідної щільності 110-130 кг/м³. Результати показують, що збільшення тиску в камері пресування зі змінним об'ємом збільшує щільність паливного ролика, тоді як більші об'єми біомаси призводять до зниження щільності. Крім того, більш високий вміст стебла льону покращує когезію та ущільнення, що призводить до більшої щільності. Ці висновки підкреслюють важливість точного налаштування технологічних параметрів для оптимізації виробництва паливних роликів. Використання стебел сільськогосподарських культур для виробництва біопалива забезпечує значні переваги для навколишнього середовища, включаючи зменшення сільськогосподарських відходів і менші викиди в результаті згоряння.

INTRODUCTION
According to data *(FAOSTAT, n.d.)*, approximately 400 million tons of agricultural plant stems are burned annually worldwide.

This practice leads to the emission of harmful substances such as solid particles (soot), nitrogen oxides, various carcinogens, and carbon monoxide, which contribute significantly to air pollution and degradation of the surface ozone layer. These pollutants exacerbate global climate change. That has been examined in depth by international researchers *(Lan et al, 2022; Amann M., 2017, Milton Halder et al., 2023)*. To mitigate these negative effects, many scholars propose efficient methods for utilizing agricultural residues *(Gatkal, N.R. et al, 2024; Kashytskyi V.P. et al, 2023).* However, among the most effective solutions is the conversion of plant biomass into biofuels *(Marian Gregory, 2016, Gageanu I. et al, 2022).* Fossil fuels represent a limited energy resource that will eventually be exhausted. Over the past several years, the significance of environmentally sustainable biofuels has become increasingly apparent. Crop Stem Biomass is a potential renewable energy source, offers notable energy content per unit mass, albeit lower than that of fossil fuels (*C.F.N, n.d.*). Its utilization as a sustainable energy alternative is a growing focus of interest among researchers. (*Mehmood Ali, et al., 2019, Jiang Y., et al, 2019*). Although significant research has been conducted on the use of agricultural biomass for energy, there is still a lack of comprehensive studies addressing the specific technical challenges associated with compacting agricultural residues into small, high-density fuel rolls (FRs).

Solid biofuels not only address the disposal problem of agricultural residues but also serve as an eco-friendly energy source. A particularly economical and straightforward approach is the production of small-sized Fuel Rolls (FRs), designed for use in modern solid-fuel heating boilers (*Yaheliuk et al., 2020*). The biomass of various crops, including flax, corn, sunflower, and grain stems, can be effectively utilized for this purpose (*Yaheliuk et al., 2021*).

The property of crop stem biomass plays a critical role in its efficient conversion into biofuels. Key characteristics to consider include Elasticity, Strength, Viscosity, Moisture Content, Density, etc. (*Hajlis G. 2004, Ibrahim Ayman, 2008, Goudenhooft C., 2018*). Analyzing and accounting for these properties allow for the optimization of equipment settings, improving processing efficiency and the quality of the biofuel produced. Reducing the elastic properties of agricultural stems is an important step in improving the efficiency of biomass processing for biofuel production. High elasticity in stems can hinder effective compaction during the production of FRs or briquettes, as the material resists deformation and may spring back after compression. Didukh, V. suggested strategy to solve this issue *(Didukh V. et al., 2022).* This research continues this work by focusing on optimizing the pressing chamber design to minimize elasticity-related losses and ensure consistent compaction of small-sized FRs.

Despite significant achievements, there remains a clear research gap in the development of efficient technologies for converting Agricultural Crop Stem Biomass into high-quality solid biofuels. Existing research has mainly focused on large-scale pellet or briquette production, with limited attention to the specific challenges of producing small-sized FRs for decentralized energy systems. There is a lack of research on designing pressing chambers that can sustainably produce small-sized, high-density FRs and determining rational parameters for processing different types of stem biomass.

The determining quality indicators for small-sized FR are the twisting density of stem biomass and the dimensions of the roll. It is advisable to use a specially designed variable volume chamber for the production of small-sized FRs. In this case, the twisting density of the stem biomass depends on the pressure created by the rollers and the volume of a linear meter of the stem biomass tape that is fed into the Variable-volume Pressing Chamber.

The aim of this study is to investigate the effect of pressing parameters on the density of small-sized FRs and determine the optimal operating conditions for a variable volume pressing chamber to ensure high fuel efficiency.

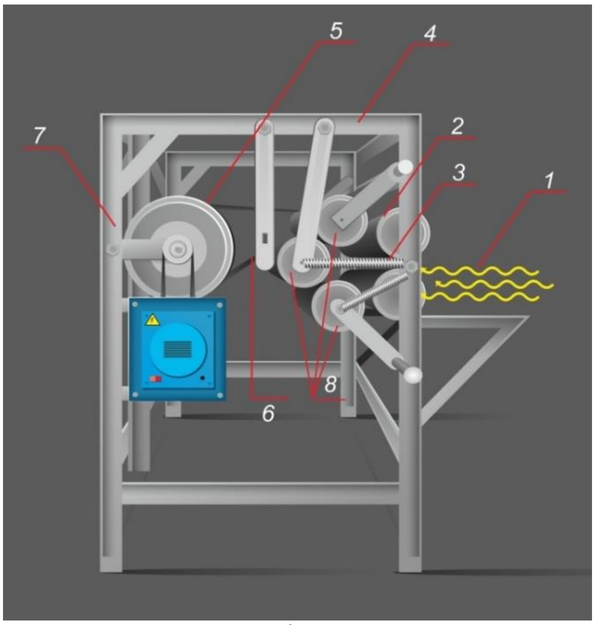
The production of small-sized Fuel Rolls represents a promising direction for sustainable biomass utilization. By addressing existing technological gaps, this research seeks to improve the viability of biofuel production, contributing to cleaner energy solutions and reducing the environmental impact of agricultural plant residues.

MATERIALS AND METHODS

Experimental equipment was designed for research. It is a Variable-volume Pressing Chamber (VPC). The formation of small-sized FRs from the Agricultural Crop Stem Biomass (ACSB) and the determination of rational technological modes for obtaining small-sized FRs of the required density was studied with its help. The scheme of the Variable-volume Pressing Chamber for studying the impact of the compression force on the density of the obtained small-sized FRs is presented in Fig.1, a, the general view in Fig.1, b.

The ACSB (1) enters the VPC between the press rollers (2), which compress the material into a denser form. The tension springs (3) ensure that the rollers apply consistent pressure while the drive belt (5), powered by the engine (7), rotates the rollers. With each rotation of the compacting rollers (8), the action of the spring (3) increases. This allows obtaining a roll of a required density. The tension roller (6) ensures the drive belt stays taut, minimizing slippage and maximizing efficiency.

The result is compacted biomass in the form of FRs, suitable for use as biofuel. This design efficiently solves issues such as reducing elasticity in plant stems, achieving consistent compaction, and producing high-density FR. The density of the formed small-sized FR is determined by the force exerted on the biomass. Two tension springs are positioned to control compaction force (Fig. 1). The lower roller axis is mounted on the frame (4), ensuring stability and alignment during operation.



a)

b)

Fig. 1 – The Variable-volume Pressing Chamber (VPC) for the formation of small-sized Fuel Roll (FR) from the Agricultural Crop Stem Biomass (ACSB)

a – scheme, b – natural appearance:

1 – biomass of agricultural crop stems; 2 – press rollers; 3 – tension springs; 4 – frame; 5 – drive belt;
6 – tension roller; 7 – engine; 8 – compacting rollers.

The advantages of the VPC are:

1. Efficient Biomass Compaction. The system effectively addresses the challenge of reducing elasticity in plant stems, creating compact, dense small-sized FRs.

2. Adjustable Density. The tension springs provide flexibility to control the compaction force, allowing the production of rolls with required density.

3. Early Roll Formation. The minimum free space between the rollers at the beginning of twisting allows to form a roll from the first turns of rollers.

It was investigated (*Yaheliuk et al., 2019*) that the operation of forming FR from the ACSB has such phases (Fig. 2):

- Initial Phase. The pressing rollers (2) compact the stem biomass (1) to form the base or "seed" of the FR. This phase has the shortest duration, as its purpose is simply to establish a FR starting point.

- Intermediate Phase (Roll Formation). The FR grows as layers of biomass are continuously wound and compacted in the pressing chamber. During this phase, the biomass is pressed further to achieve an intermediate level of density.

- Final Phase (Maximum Density). The tension springs (3) enable the compacting rollers (4) to adjust their position as the FR grows in size and density. The biomass is wound tightly to ensure maximum density, with the rollers continuously applying pressure. The springs allow the compacting rollers to move outward as the radius of the FR increases, maintaining consistent pressure throughout the process.

The rollers are designed to move outward to accommodate the increasing size of the FR, thanks to the flexibility provided by the tension springs (3).

For the production of FR, the biomass of wheat, rye, flax stems (ACSB) were used in different proportions as a raw material (Table 1). The stems were destroyed before twisting (*Didukh V. et al, 2022*). The initial relative humidity of the crop stem biomass material was 8.5-15*%.*

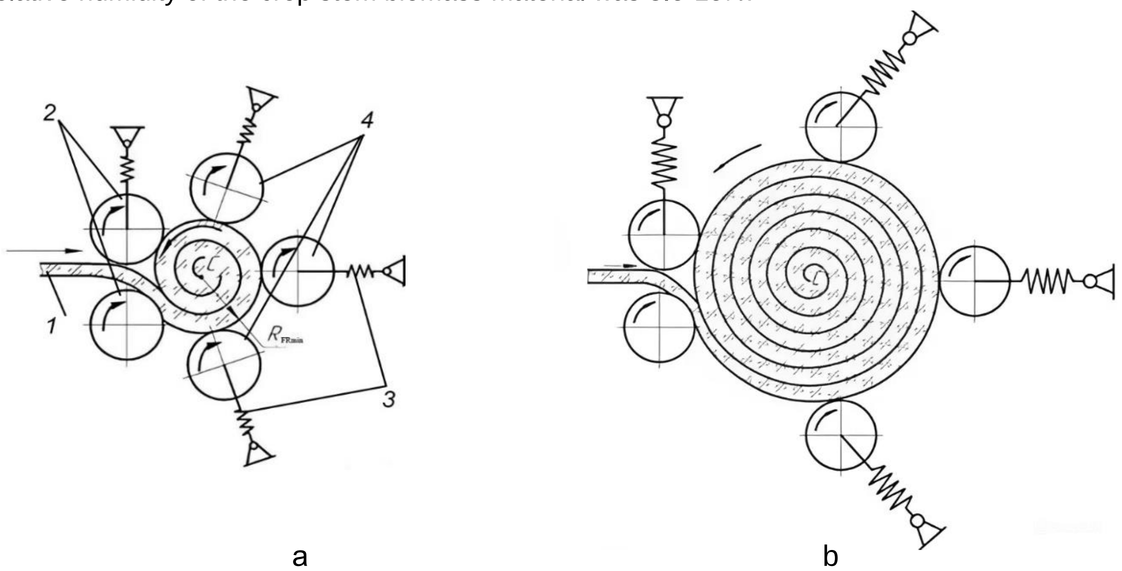


Fig. 2 – The scheme of the formation of FR from the ACSB in the VPC
a - the Initial Phase of the formation of the FR, b - the Final Phase of the formation of the FR:
1 – biomass of agricultural crop stems; 2 – press rollers; 3 – tension springs; 4 –compacting rollers

The complexity of forming rolls from ACSB is associated with the elastic properties of plants. The stem mass obtained after the separation of seeds is not destroyed much under the action of the threshing machine. Therefore, its elastic properties are high. To preserve the shape of the roll, it is necessary to use binding agent (rope). But this is not permissible for small-sized FRs. Therefore, it is necessary, besides other, to use fiber stem materials, as flax stems, for the production of FRs.

Table 1

Content of flax stems in the Agricultural Crop Stem Biomass (ACSB)

ACSB	FR75/25	FR50/50	FR25/75
Flax stems, *%*	*75*	*50*	*25*
Wheat, rye, *%*	*25*	*50*	*75*

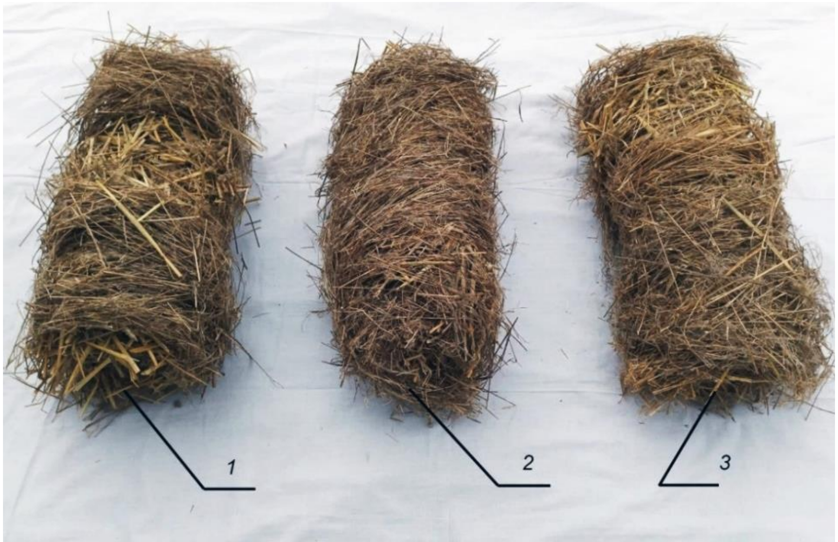


Fig. 3 – The FRs from biomass of agricultural plants stem:
1 – FR25/75; 2 –FR75/25; 3 – FR50/50

Density is a determining indicator of quality for FR. It affects the calorific value of FR, their transportation and storage.

The following technological parameters were determined to influence the density of FR: the pressure created by the rollers in the Variable-volume Pressing Chamber (*P,* MPa), the volume of a linear meter of ACSB fed into the VPC (*v,* m^3), the content of flax stems in the ACSB fed into the VPC on the density of the obtained FR (*m, %*).

The study of the influence of the pressure in the pressing chamber of variable volume and the volume of a linear meter of the stem biomass of agricultural plants entering the pressing chamber on the density of the FR was carried out by the method of mathematical planning of the experiment. *(Box G.E.P., Behnken D.W., 1960; Aziz R.A., Aziz S.A., 2018)*.

The purpose of the experiment was to determine the density of the formed FR while varying the technological parameters: the pressure created by the rollers in the VPC (*P,* MPa), the volume of a linear meter of the Agricultural Crop Stem Biomass, which is fed into the VPC (*v,* m^3) and the content of flax stems in the ACSB fed into the VPC on the density of the obtained FR (*m, %*) (Table 2).

Table 2

Variables and Their Levels in Box-Behnken Design

Levels of variation	X, pressure P (MPa)	X2, volume of a linear meter ACSB V, (m^3)	X3, content of flax stems m, (%)
Upper (+1)	*0.60*	*0.8*	*75*
Main (0)	*0.55*	*0.7*	*50*
Lower (-1)	*0.50*	*0.6*	*25*
Range of variation	*0.05*	*0.1*	*25*

Table 3 shows the planning matrix of the three-factor experiment according to the Box-Behnken design (*Box G.E.P., Behnken D. W., 1960*). Matrix is presented in a coded format. The order of experiments was determined using a table of random numbers.

Table 3

Design of experiment

Run	Pressure P (MPa)	Volume of a linear meter ACSB V (m^3)	Content of flax stems m, (%)
1	*1*	*1*	*0*
2	*-1*	*1*	*0*
3	*1*	*-1*	*0*
4	*-1*	*-1*	*0*
5	*1*	*0*	*1*
6	*-1*	*0*	*1*
7	*1*	*0*	*-1*
8	*-1*	*0*	*-1*
9	*0*	*1*	*1*
10	*0*	*-1*	*1*
11	*0*	*1*	*-1*
12	*0*	*-1*	*-1*
13	*0*	*0*	*0*
14	*0*	*0*	*0*
15	*0*	*0*	*0*

The response function, representing the density of the FR, is expressed in the factor space as a nonlinear regression equation (1):

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1X_2 + b_{13} X_1X_3 + b_{23} X_2X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 \quad (1)$$

where:

Y is the response (density of the FR, ρ), and X_1, X_2, X_3 are the coded variables for P, V, and m.

RESULTS AND DISCUSSION

As a result of the research (Table 4) data have been obtained on the density of the Fuel Roll (FR), *ρ, kg/m³,* that depends on the pressure created by the rollers in the Variable-volume Pressing Chamber (VPC), (*P,* MPa), the volume of a linear meter of the Agricultural Crop Stem Biomass (ACSB), which is fed into the VPC (*v,* m^3) and the flax stem content in the ACSB (*m, %*).

Table 4

Box-Behnken design scheme and the density of the FR response values

Run	P (MPa)	V (m^3)	m (%)	ρ (kg/m^3)
1	*0.60*	*0.8*	*50*	*119.067*
2	*0.50*	*0.8*	*50*	*107.167*
3	*0.60*	*0.6*	*50*	*124.933*
4	*0.50*	*0.6*	*50*	*113.233*
5	*0.60*	*0.7*	*75*	*128.167*
6	*0.50*	*0.7*	*75*	*115.133*
7	*0.60*	*0.7*	*25*	*112.533*
8	*0.50*	*0.7*	*25*	*103.100*
9	*0.55*	*0.8*	*75*	*122.300*
10	*0.55*	*0.6*	*75*	*127.233*
11	*0.55*	*0.8*	*25*	*106.100*
12	*0.55*	*0.6*	*25*	*112.067*
13	*0,55*	*0.7*	*50*	*119.400*
14	*0,55*	*0.7*	*50*	*119.200*
15	*0.55*	*0.7*	*50*	*118.900*

The experiment conducted according to the Box-Behnken design enabled the development of a mathematical model describing the dependence of FR density on technological parameters in the form of a regression equation. The results of three-factor experiments were processed according to a second-order, three-level design using a program developed in the Mathcad environment. The Box-Behnken experimental design allowed for an efficient investigation of the influence of three independent variables (technological parameters) on the response variable (density of the formed FR) (*Montgomery C. Douglas, 2013*). The regression model in coded factors is presented as follows (2):

$$\rho = 119.2 + 5.8X_1 - 2.8X_2 + 7.4X_3 + 0.9X_1X_3 - 2.6X_1^2 - 1.8X_3^2 \quad (2)$$

The homogeneity of the variance series was evaluated using the Cochrane criterion. The calculated value $G_{res} = 0.19$ was compared to the tabular value $G_{tab} = 0.335$ (for $\alpha = 0.05$, $f_1 = 10, f_2 = 3$) and an alternative tabular value of 0.373. Since $G_{res} < G_{tab}$ it can be concluded that the experimental process is reproducible. The adequacy of the regression equation (2) was verified using Fisher's *F*-test. The calculated *F-statistic* value was $F_{res} = 16.196$, based on the variance of inadequacy $S_{nead}^2 = 1.026$ and the variance of reproducibility $S_y^2 = 0.063$. The tabular value of the Fisher statistic at a 5% significance level ($= 0.05$) with degrees of freedom $f_1 = 2, f_2 = 7$ was $F_{table} = 19.4$. Since $F_{res} < F_{tab}$ the regression model was confirmed to be adequate.

Using the given central levels (*P_0=0.55* MPa, *V_0=0.7* m^3, *m_0=50 %*) and the corresponding ranges of variation (Δ*P=0.05,* ΔV=0.1, Δm=25), the regression equation in coded factors was converted into natural variables. The resulting equation, expressed in natural factors P (pressure, MPa), V (volume of a linear meter ACSB, m^3), and m (content of flax stems, %), is as follows (3):

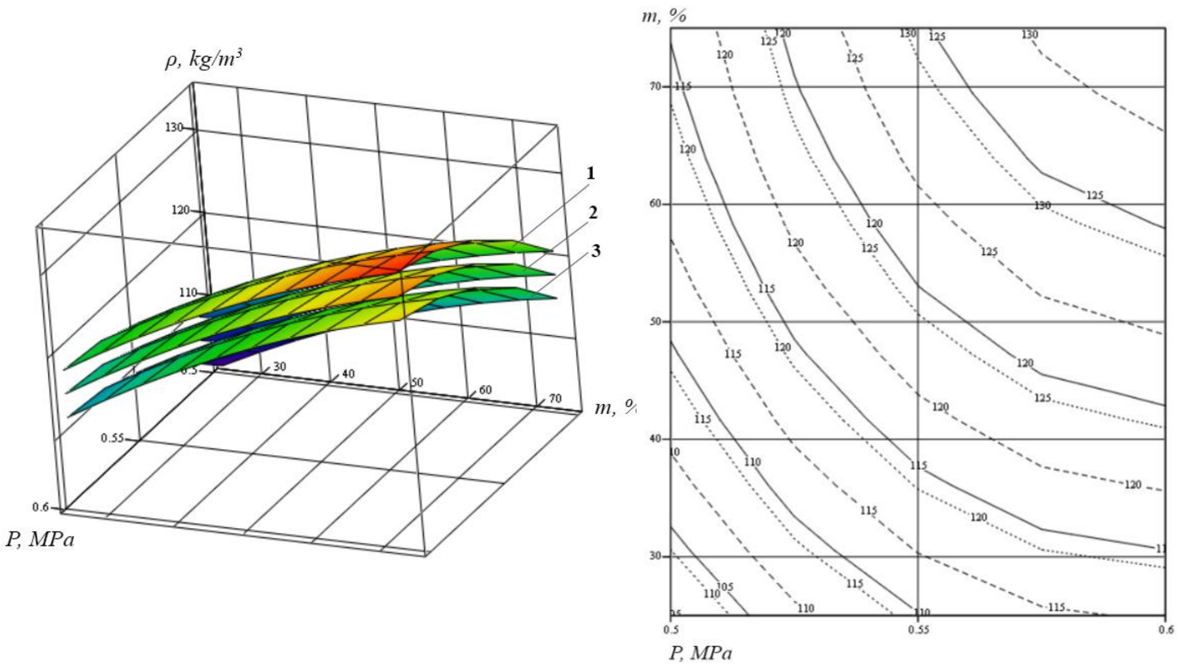
$$\rho = -224.4 + 1240P - 28.5V + 0.19m + 0.72P * m - 1038.2P^2 - 0.003m^2 \quad (3)$$

This equation accounts for the scaling and centering of the factors, ensuring the model is directly applicable to the original experimental conditions. The regression coefficients reflect the influence of the natural variables on the response (density of the FR, *ρ*), making the equation suitable for practical interpretation and optimization. The response surfaces (Fig.4, a and Fig.5, a) and their contour plots (Fig.4, b and Fig.5, b) are constructed using the regression equation (3).

The response surface (Fig.4a) and contour plot (Fig.4b) illustrate the relationship between the density of FR and two variables: the pressure applied by rollers in the (*P,* MPa) and the volume of a linear meter of ACSB (*V,* m³*)* fed into the chamber. The response surface shows a clear trend where increasing the pressure in the pressing chamber (*P*) leads to a significant increase in the density of the FR.

This is evident from the upward slope of the surface as pressure values increase. Conversely, increasing the volume of biomass (*V*) tends to decrease the density, as represented by the downward slope of the surface in the direction of larger biomass volumes. This interplay indicates that higher pressure compresses the material more effectively, while larger volumes of biomass tend to resist compression, leading to lower densities.

The contour plot (Fig.4b) provides a detailed view of how combinations of pressure and biomass volume influence density. The interaction between pressure and biomass volume indicates that maintaining a moderate biomass volume (around 0.6–0.7 m³) while increasing pressure to values near 0.58–0.6 MPa yields the highest density. This is important for achieving FR with structural integrity, as density directly correlates with combustion efficiency and energy potential.



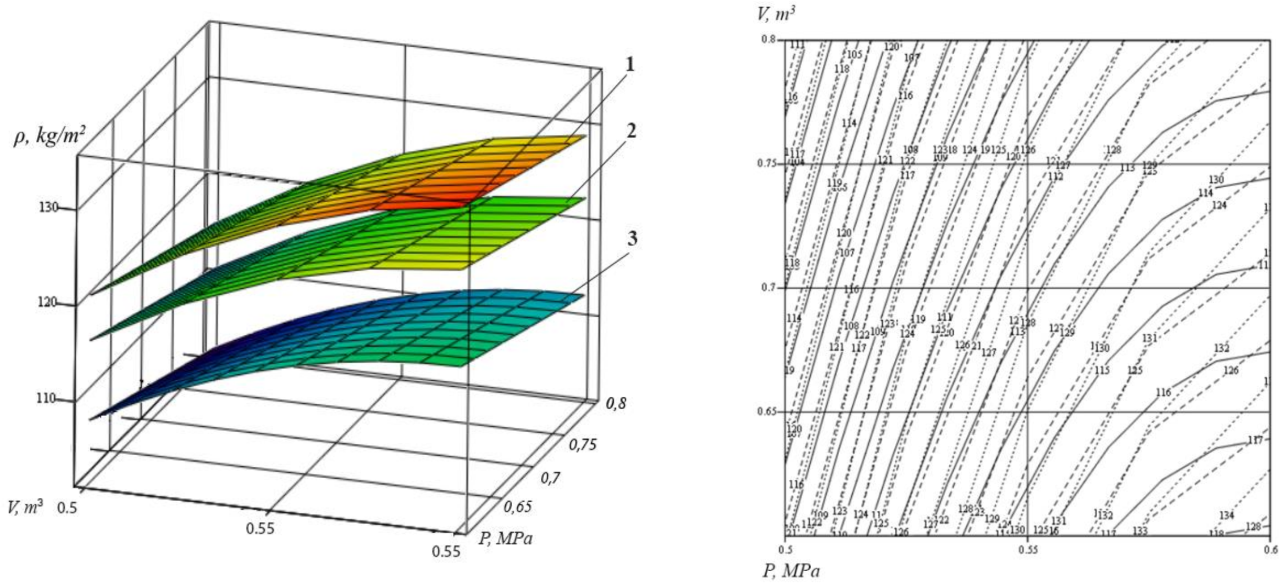
a) b)

Fig. 4 - The results of the study of the dependence of the FR density on the pressure created by the rollers in the VPC (*P,* MPa) and the volume of a linear meter of the ACSB (*V,* m^3)

a –response surface; b - contour plot of the response surface:
1 – V =0.6 m^3; 2 – V=0.7 m^3; 3 – V=0.8 m^3

The images (Fig. 5 a, b) showcase visualization of a study analyzing the dependence of FR density (*ρ*) on the pressure (*P,* MPa) exerted by rollers in a VPC and the flax stem content in FR (*m, %*) for three different material compositions: FR75/25, FR50/50, and FR25/75. For all material compositions, the density increases with higher rollers pressure (*P*). The FR75/25 composition, which has a higher proportion of flax stems, results in higher densities compared to FR50/50 and FR25/75 under similar conditions. This is due to the fibrous nature of flax, which enhances material cohesion during compression.

The contour plot (Fig.5 b) provides a top-down view of the response surface, showing density lines as a function of P and V. These contours clearly illustrate how the density changes within the defined parameter space. The spacing of the contour lines suggests that the effect of increasing *P* on *ρ* becomes less pronounced at higher pressures, indicating at a potential saturation point in compaction efficiency.



a) b)

Fig. 4 - The results of the study of the dependence of the FR density on the pressure created by the rollers in the VPC (*P, MPa*) and content of flax stems (m, %)

a –response surface; b - contour plot of the response surface:

1 – FR75/25, 2 – FR50/50, 3 – FR25/75

The studied *(C.F.N, n.d.)* data show (Table 5) that flax stems are a good source of biomass energy with an energy potential of 18 MJ/kg. Compared to traditional fossil fuels such as coal (22 MJ/kg) or fuel oil (37 MJ/kg), this is less. However, such an energy potential of flax stems makes it possible to compare flax-based FR with wood fuels (16-20.5 MJ/kg).

Flax and wheat straw are structurally similar and possess the same energy value, making them compatible for mixing. This compatibility ensures uniform energy production, which is critical for efficient combustion. Additionally, their fibrous nature enhances mechanical properties such as cohesion and density when compressed into fuel rolls. The abundant availability of these materials as by-products of agricultural processes provides economic and environmental benefits, as their use for energy production reduces waste while offering a sustainable energy source.

Table 5

The energy potential of various types of sources (*C.F.N, n.d.*)

Sources	**Traditional sources of energy**		**Agriculture biomass**							**Wood biomass**			
	Hard coal	Fuel oil	Corn	Flax stem	Wheat straw	Sunflower stem	Rape pomace	Sunflower husks	Cotton stems	Basket willow	Poplar	Beech	Fir
Energy potential, *MJ/kg*	22	42	15	18	15	15	19	18	17,5	18,5	16	18	20,5

The study presents a regression model for predicting the density of fuel rolls (FRs) produced from agricultural crop stem biomass (ACSB). To ensure efficient production of FRs from ACSB, the following technological parameters are recommended:

1. Compaction Pressure in the Variable-Volume Pressing Chamber (VPC). Recommended pressure ranges for different blends are:
    - FR75/25 (75% flax stems, 25% other materials): 0.50–0.55 MPa;
    - FR50/50 (50% flax stems, 50% other materials): 0.45–0.55 MPa;
    - FR25/75 (25% flax stems, 75% other materials): 0.40–0.50 MPa.

Higher flax stem content requires slightly higher pressures to achieve uniform density due to its fibrous structure. Within these pressure ranges, densities of 110–130 kg/m³ can be achieved, meeting mechanical stability and energy performance requirements.

2. The volume of a linear meter of the Agricultural Crop Stem Biomass. Optimal biomass volumes for achieving the required density without compromising material cohesion or creating excessive porosity are:

- FR75/25: 0.7–0.75 m³;
- FR50/50: 0.65–0.7 m³;
- FR25/75: 0.65–0.7 m³.

By maintaining compaction pressures of 0.45–0.55 MPa, biomass volumes of 0.65–0.75 m³ of a linear meter of the ACSB, and rational blending ratios of flax stems with complementary biomass, fuel rolls can achieve densities of 110–130 *kg/m³* and energy potentials of 16–18 MJ/kg. These optimized parameters ensure a balance of mechanical strength, energy efficiency, and resource sustainability, positioning flax-based FR as a competitive and eco-friendly option for bioenergy production.

CONCLUSIONS

The study highlights the significant potential of agricultural crop stem biomass (ACSB) as a sustainable and environmentally friendly resource for biofuel production. By optimizing technological parameters, it is possible to produce small-sized Fuel Rolls (FRs) with high density and substantial energy potential. Regression analysis indicates that achieving densities between 110 and 130 kg/m³ requires compaction pressures of 0.40–0.55 MPa and feed volume of 0.65–0.75 m³ of a linear meter of the Agricultural Crop Stem Biomass depending on the blending ratio of flax stems with other biomass materials. Higher flax stem content, due to its fibrous properties, demands increased pressure to ensure uniform density and material cohesion.

Flax-based FRs have energy potentials of 16–18 MJ/kg, comparable to wood fuels and sufficient for modern solid-fuel heating systems. The introduction of the Variable-Volume Pressing Chamber (VPC) successfully addressed challenges such as stem elasticity, allowing for efficient compaction and consistent density throughout production. These findings underscore the importance of integrating rational compaction pressures, biomass volumes, and blending ratios to achieve a balance between energy efficiency, mechanical strength, and sustainability.

By converting agricultural residues into biofuels, the study provides a practical solution to mitigate environmental pollution from residue burning, reduce waste, and promote renewable energy. Fuel rolls represent a competitive and sustainable alternative to traditional fossil fuels, contributing to cleaner energy solutions and advancing the global transition towards more sustainable energy practices.

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