







## Article

# Energy Parameters of Miscanthus Biomass Pellets Supplemented with Copra Meal in Terms of Energy Consumption during the Pressure Agglomeration Process

Joanna Szyszlak-Bargłowicz <sup>1</sup>, Tomasz Słowik <sup>1,\*</sup>, Grzegorz Zajac <sup>1</sup>, Agata Blicharz-Kania <sup>2</sup>, Beata Zdybel <sup>2</sup>, Dariusz Andrejko <sup>2</sup> and Sławomir Obidziński <sup>3</sup>

<sup>1</sup> Department of Power Engineering and Transportation, Faculty of Production Engineering, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland; joanna.szyszlak@up.lublin.pl (J.S.-B.); grzegorz.zajac@up.lublin.pl (G.Z.)

<sup>2</sup> Department of Biological Bases of Food and Feed Technologies, Faculty of Production Engineering, University of Life Sciences, Głęboka 28, 20-612 Lublin, Poland; agata.kania@up.lublin.pl (A.B.-K.); beata.zdybel@up.lublin.pl (B.Z.); dariusz.andrejko@up.lublin.pl (D.A.)

<sup>3</sup> Faculty of Civil Engineering and Environmental Sciences, Białystok University of Technology, Wiejska 45E, 15-351 Białystok, Poland; s.obidzinski@pb.edu.pl

\* Correspondence: tomasz.slowik@up.lublin.pl; Tel.: +48-81-531-97-19



**Citation:** Szyszlak-Bargłowicz, J.; Słowik, T.; Zajac, G.; Blicharz-Kania, A.; Zdybel, B.; Andrejko, D.; Obidziński, S. Energy Parameters of Miscanthus Biomass Pellets Supplemented with Copra Meal in Terms of Energy Consumption during the Pressure Agglomeration Process. *Energies* **2021**, *14*, 4167. <https://doi.org/10.3390/en14144167>

Academic Editors: Marcin Jewiarz and Marek Wróbel

Received: 7 June 2021

Accepted: 8 July 2021

Published: 10 July 2021

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**Abstract:** The process of pelleting miscanthus biomass often encounters issues related to the low durability of the obtained pellets and high energy inputs. To solve these issues, the use of copra meal as a supplement is proposed. This paper presents the results of research on energy parameters of miscanthus biomass pellets supplemented with copra meal in terms of energy consumption in the pressure agglomeration process. As part of this research, the energy parameters of miscanthus biomass, copra meal biomass, and their blends were characterized. Next, the raw materials were used for the production of pellets in the pressure agglomeration process. The investigations included proximate and ultimate analysis and estimation of heating values. Moreover, the total fat content, mechanical durability, kinetic strength, and bulk density were determined, and the energy consumption in the pelleting process was assessed. The results indicate that the energy consumption in the miscanthus biomass pelleting process can be substantially reduced by adding copra meal as a biocomponent. When the copra meal addition did not exceed 30%, the pellets exhibited over 95% durability, over 1200 kg·m<sup>-3</sup> density, and over 417 kg·m<sup>-3</sup> bulk density. Given the 44% reduction in energy consumption in the pellet production process and the energy efficiency of 4815 Wh·kg<sup>-1</sup> determined in this study, copra meal may be an interesting material for use as an additive in the production of miscanthus biomass pellets.

**Keywords:** miscanthus; biomass; pelleting; energy consumption

## 1. Introduction

Due to the growing demand for green energy, biomass fuels such as wood pellets are being increasingly used, especially in low-power systems. However, the growing demand for biofuel necessitates a search for alternative raw materials, e.g., energy crops [1] and agri-food waste (waste biomass) [2–4]. The use of the latter raw material in particular is an optimal approach to solve issues related to waste management in accordance with the principles of sustainable development [5].

Perennial energy plants have a huge technical potential that can be used for energy purposes. One of these plants is the giant miscanthus (*Miscanthus × giganteus*). Miscanthus has a high potential yield, low nutrient requirements, and a high efficiency of solar energy conversion to biomass. According to 2018 data, miscanthus is grown in the EU in an area of around 20,000 ha, of which around half is in the UK [6–8]. The biomass of this plant can be used as fuel in incinerators [9], and the production of miscanthus biofuels is also being

studied [10]. Recent literature reports that the most advantageous method of producing energy from miscanthus is burning its biomass [11,12].

To concentrate energy, miscanthus biomass should undergo pressure agglomeration processes, including pelleting. However, the pellets obtained in this process often do not achieve the required durability, which is important for maintaining their quality during transport and handling [13]. Low durability results in a high level of crumbling. In particular, dust and fine particles from crushed pellets may adversely affect the operation of the feeders and the burner.

Research on miscanthus biomass pelleting is widely reported in the literature; however, these studies are not comprehensive and do not cover the issues of energy consumption in the compaction process. Moon et al. [14] did not obtain pellets of satisfactory quality in the first stage of their research in pilot studies. Mani et al. [15] indicated that a lower lignin content and poor bonding between particles during the formation of lignocellulosic granules are the reasons for the lower durability of the obtained pellets.

Factors that are often considered are the addition of a binder and mixtures of different raw materials, as they affect the quality of pellets during the pelleting process. These factors may have a positive effect on pellet strength, reduction of process energy consumption, and efficiency of the combustion system [16–19].

When choosing a binder, its cost and environmental friendliness as well as pelleting energy consumption should be considered. From this point of view, the use of waste bio-mass as a binder in the production of pellets seems to be a reasonable approach.

One of the waste materials that is generated in the food industry is copra meal. It is a byproduct of coconut oil extraction from coconut kernels. World production of copra meal is estimated at 1,931,000 Mg [20]. Copra meal is mainly used in the feed industry because of its affordable price and composition. However, its use in animal nutrition is limited and requires additional operations to improve the nutritional properties [21,22]. Therefore, the possibility of a more effective use of copra meal should be sought. One option could be to use this raw material as a biofuel. The available literature lacks information on the possible use of copra meal as an alternative energy source. This prompted us to undertake experimental research on the use of copra meal as an additive for the production of miscanthus biomass pellets.

The main goals of this study were (1) characterization of the energy parameters of miscanthus biomass, copra meal, and their mixtures, (2) assessment of pellets produced from the mixtures, i.e., determination of density, durability, mechanical strength, and bulk density, and (3) verification of the best relationship between the physicochemical, energetic, and mechanical properties of the granulate.

## 2. Materials and Methods

### 2.1. Research Material

The research material consisted of dried copra meal and miscanthus shoots. The copra meal raw material was obtained from a food processing plant that produces coconut oil (PHU “Karol”). For the research, the raw material was crushed using a laboratory shredder (FW100 model) (ChemLand, Stargard, Poland).

The biomass of the giant miscanthus (*Miscanthus × giganteus*) was obtained from a research plot established as part of an experiment in the town of Lipsko, Poland. Harvested shoots were shredded into 5–8 mm fragments (Figure 1a,b).

A detailed research design is presented in Figure 2.



Figure 1. Experimental materials: (a) fragmented miscanthus biomass, (b) copra meal.

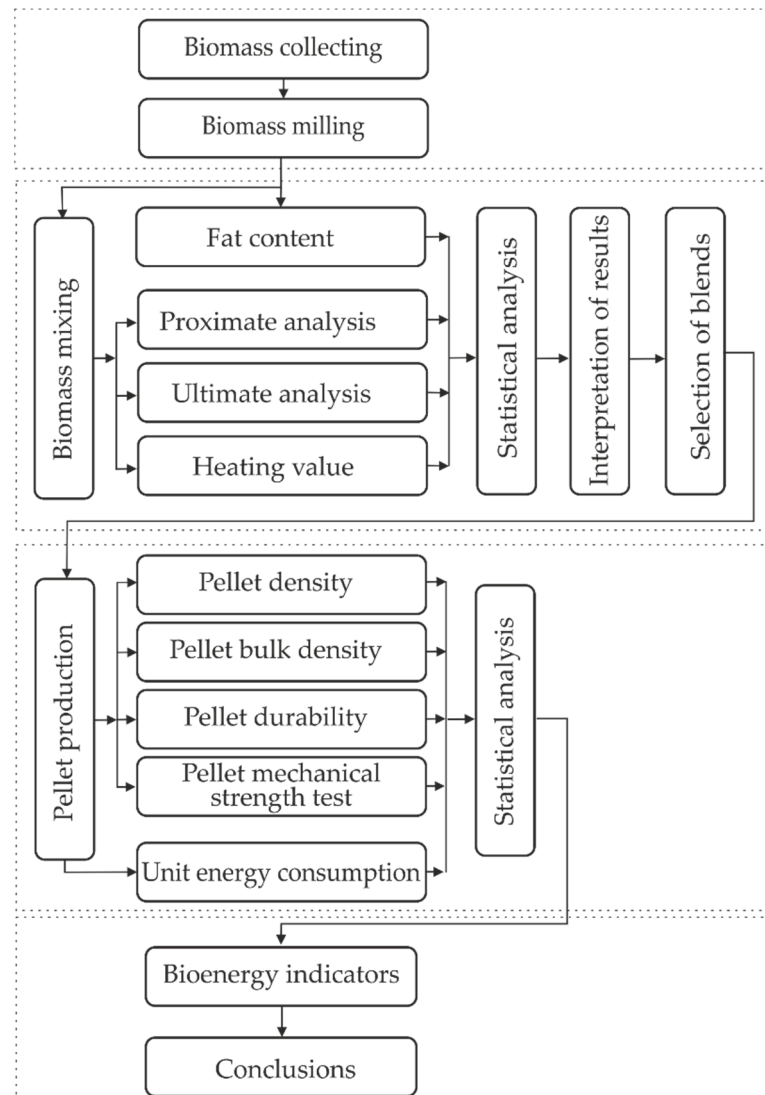


Figure 2. Research design.

## 2.2. Preparation of Samples

The research material was prepared in accordance with the EN ISO 14780:2017 standard. The miscanthus and copra meal were ground in an analytical mill (IKA A11, IKA-Werke GmbH & Co. KG, Staufen, Germany) to fractions with a particle size ranging from 0.5 to 1.0 mm. The materials were blended in various weight proportions:

- 90% miscanthus and 10% copra—M90C10,
- 80% miscanthus and 20% copra—M80C20,
- 70% miscanthus and 30% copra—M70C30,
- 60% miscanthus and 40% copra—M60C40,
- 50% miscanthus and 50% copra—M50C50,
- 40% miscanthus and 60% copra—M60C40.

Miscanthus M100C0 and copra meal M0C100 samples were also analyzed.

## 2.3. Heating Value Estimation and Ultimate and Proximate Analysis

The C and H content in dry biomass was analyzed by high-temperature combustion with IR detection, while the N content was determined with the catarometric method (ISO 16948). The S content was determined by high-temperature combustion with IR detection in accordance with EN ISO 16994 by using a CHNS 628 elemental analyzer (LECO Corporation, Saint Joseph, MI, USA). Moisture, volatile matter, and ash contents were assessed using a thermogravimetric analyzer TGA 701 (LECO Corporation) in accordance with standards EN ISO 18134, EN ISO 18123, and EN ISO 18122, respectively. A calorimeter (AC 600, LECO Corporation, Saint Joseph, MI, USA) was used to measure the higher heating value in accordance with ISO 1928. The lower heating value was calculated based on the higher heating value. All tests were performed in a minimum of three replicates.

## 2.4. Determination of Fat Content

The total fat content was determined in the raw materials used in the study. The analysis was performed with the continuous ether extraction method using a Soxtec<sup>TM</sup> 8000 device (Foss Analytical AB, Höganäs, Sweden) and the AN 310 application. The analyses were performed in three replicates.

## 2.5. Pellet Production

The process of densification of the investigated blend of miscanthus with copra meal was performed on a work stand, whose main component was a BRICOL ZSJ25 flat-die pellet mill (Człuchów, Poland). The maximum capacity of the pellet mill was 100 kg·h<sup>-1</sup>; the rotational speed of the die was 260 rpm; the number of rolls was 2; and the diameter and length of the channels were 6 mm and 30 mm, respectively, with an L/D ratio of 5.0. Granulation tests began after preheating the matrix to 85 °C. The temperature of the die during compaction was constantly monitored and maintained at a constant level (±5 °C). Approximately 50 kg samples were prepared.

The power consumption was recorded during the pellet mill work by using a KEW6310 analyzer (KYORITSU, Tokyo, Japan). The pelleting energy consumption was recorded for each of the blends after reaching the thermal equilibrium in the working system (temperature: 85 °C). The recorded data were analyzed using a dedicated KEW PQA MASTER program.

## 2.6. Properties of Pellets

### 2.6.1. Pellet Density

Pellet density was determined with the hydrostatic method in accordance with the ISO 18847 standard. A KIT-85 density determination kit for solids and liquids (Radwag, Radom, Poland) and a Radwag X3.Y analytical balance (Radwag, Radom, Poland) with a measurement accuracy of ±0.0001 g were used. A mixture of water and a wetting agent (Triton X-100) in water at a concentration of 1.5 g·L<sup>-1</sup> was used as the standard liquid. The analyses were carried out in five replicates, and the results were expressed as a mean value.

### 2.6.2. Pellet Bulk Density

The bulk density of the pellets was determined in accordance with ISO 17828. The sample was placed in a 5 l cylinder. Its surface was smoothed toward the edge of the cylinder, and the cylinder with the sample was then weighed. The bulk density was defined as the ratio of the sample weight to the cylinder volume.

### 2.6.3. Mechanical Durability of Pellets

Pellet durability was tested using the apparatus described in EN 17831-1:2015. A pre-sieved  $500 \pm 10$  g sample was placed in the tumbling device set at  $50 \pm 2$  rpm for 500 rotations. The remaining sample was removed and manually sieved. The material remaining on the sieve was weighed. The process was repeated 5 times for each pellet type. The durability was calculated as follows:

$$DU = \frac{m_A}{m_E}, [\%] \quad (1)$$

where:

$m_A$ —final mass (g),

$m_E$ —initial mass (g).

### 2.6.4. Pellet Mechanical Strength Test

The determinations were performed using the ZwickRoell Z0.5 testing machine (ZwickRoell AG, BT1-FR0.5TN.D14, Ulm, Germany) using a measuring head with a maximum pressing force of 500 N (travel speed— $5 \text{ mm} \cdot \text{min}^{-1}$ ). The testXpert II software was used for the analysis. Randomly selected samples were used in the analyses [23].

Axial compression (AC), three-point compression (3PC), and point compression (PC) tests were used [24]. The samples were aligned manually to have parallel tips and the same length. The test was conducted until destruction of the sample. The compressive strength  $\sigma$  [MPa] was calculated as the maximum pressure applied to the sample surface during compression [25]. All determinations were performed under the same conditions in five replicates.

In the AC test, a single sample ( $15 \pm 0.5$  mm long) was placed vertically on a stationary plate and compressed axially with a flat cylindrical attachment with a diameter of 25.4 mm [23]. In the 3PC test, the sample was placed horizontally on two supports with a span of 20 mm. The load was applied from top to bottom toward the center of the sample. The PC test was performed using the Warner–Bratzler attachment for testing cylindrical samples [26]. A single pellet ( $15 \pm 0.5$  mm long) was placed horizontally on a stationary plate, and the load was applied to its central part

## 2.7. Statistical Analysis

Statistical analysis was conducted using ANOVA with post hoc tests for homogeneous groups (groups of means, with no statistically significant difference between them at the significant  $\alpha$  level) based on Tukey's test. A significance level  $\alpha = 0.05$  was assumed for inference.

## 3. Results and Discussion

### 3.1. Properties of Raw Materials and Mixtures

The results of the proximate and ultimate analysis and heating value estimation of the raw materials and their blends are presented in Table 1.

**Table 1.** Results of proximate and ultimate analysis and heating value estimation.

Parameter	M100C0	M0C100	M90C10	M80C20	M70C30	M60C40	M50C50	M40C60
Moisture [%]	7.20 ±0.05 <sup>h</sup>	5.43 ±0.02 <sup>a</sup>	6.76 ±0.03 <sup>g</sup>	6.56 ±0.03 <sup>f</sup>	6.41 ±0.02 <sup>e</sup>	6.24 ±0.03 <sup>d</sup>	6.06 ±0.06 <sup>c</sup>	5.87 ±0.02 <sup>b</sup>
Volatile substances [%]	73.61 ±0.29 <sup>d</sup>	75.62 ±0.15 <sup>b</sup>	74.93 ±0.43 <sup>abc</sup>	74.92 ±0.27 <sup>abc</sup>	74.56 ±0.43 <sup>ac</sup>	75.07 ±0.18 <sup>ab</sup>	74.18 ±0.10 <sup>cd</sup>	75.23 ±0.42 <sup>ab</sup>
Ash [%]	2.36 ±0.14 <sup>a</sup>	5.46 ±0.04 <sup>e</sup>	2.70 ±0.04 <sup>d</sup>	2.78 ±0.07 <sup>a</sup>	3.09 ±0.15 <sup>b</sup>	3.11 ±0.02 <sup>b</sup>	3.72 ±0.06 <sup>c</sup>	3.80 ±0.11 <sup>c</sup>
Fixed carbon [%]	16.40 ±0.23 <sup>b</sup>	13.49 ±0.18 <sup>d</sup>	15.94 ±0.37 <sup>ab</sup>	15.82 ±0.17 <sup>abc</sup>	15.94 ±0.31 <sup>ab</sup>	15.58 ±0.18 <sup>ac</sup>	16.03 ±0.11 <sup>ab</sup>	15.10 ±0.49 <sup>c</sup>
C [%]	48.45 ±0.11 <sup>e</sup>	46.60 ±0.07 <sup>a</sup>	47.90 ±0.07 <sup>d</sup>	47.83 ±0.02 <sup>cd</sup>	47.36 ±0.04 <sup>bc</sup>	47.26 ±0.01 <sup>b</sup>	46.87 ±0.04 <sup>ab</sup>	46.43 ±0.53 <sup>a</sup>
H [%]	6.09 ±0.04 <sup>e</sup>	7.02 ±0.03 <sup>f</sup>	6.33 ±0.04 <sup>a</sup>	6.42 ±0.01 <sup>a</sup>	6.54 ±0.06 <sup>b</sup>	6.64 ±0.01 <sup>bc</sup>	6.68 ±0.05 <sup>cd</sup>	6.78 ±0.02 <sup>d</sup>
N [%]	0.240 ±0.003 <sup>a</sup>	3.155 ±0.021 <sup>h</sup>	0.371 ±0.008 <sup>b</sup>	0.492 ±0.003 <sup>c</sup>	0.554 ±0.021 <sup>d</sup>	0.718 ±0.017 <sup>e</sup>	0.949 ±0.029 <sup>f</sup>	1.325 ±0.029 <sup>g</sup>
S [%]	0.004 ±0.0001 <sup>b</sup>	0.1250 ±0.002 <sup>g</sup>	0.008 ±0.001 <sup>c</sup>	0.011 ±0.0005 <sup>d</sup>	0.017 ±0.001 <sup>a</sup>	0.019 ±0.0005 <sup>a</sup>	0.027 ±0.0005 <sup>e</sup>	0.0450 ±0.001 <sup>f</sup>
HHV [kJ·kg <sup>-1</sup> ]	17578 ±20.0 <sup>c</sup>	19606 ±50.6 <sup>d</sup>	17801 ±50.5 <sup>a</sup>	17853 ±78.8 <sup>a</sup>	17924 ±28.6 <sup>ab</sup>	18023 ±9.5 <sup>b</sup>	18046 ±49.9 <sup>b</sup>	18221 ±40.0 <sup>c</sup>
LHV [kJ·kg <sup>-1</sup> ]	16307 ±20.0 <sup>c</sup>	18384 ±50.6 <sup>d</sup>	16542 ±50.0 <sup>a</sup>	16588 ±78.8 <sup>a</sup>	16661 ±28.6 <sup>ab</sup>	16762 ±9.8 <sup>b</sup>	16789 ±49.9 <sup>b</sup>	16967 ±40.0 <sup>c</sup>

±: Standard deviation; mean values with the same letter in a row are not significantly different at  $p < 0.05$  in Tukey's HSD test.

Moisture M of the copra meal and miscanthus biomass was calculated to be 5.43% and 7.20%, respectively. It decreased along with the increase in the copra meal proportion in the blends. Statistical analysis confirmed the significance of these changes. A noteworthy finding is that each 10% increase in the copra meal amount resulted in a significant reduction in moisture in all blends (different homogeneous groups).

The content of volatile substances (VS) ranged from 73.61% in the miscanthus biomass to 75.62% in the copra meal. Significant changes were observed in this parameter in the 10% copra meal M90C100 variant. However, no significant differences were observed in the volatile matter content for blends containing 40–100% copra meal (M40C60–M0C100).

The ash (A) content in the basic raw materials was 2.36% in the miscanthus biomass and 5.46% in the copra meal. In the blends, the addition of 10% copra meal caused a significant increase in the A content in the M90C100 sample. However, the mean A contents in the M70C30 and M60C40 blends as well as in the M50C50 and M40C60 blends were assigned to the same homogeneous groups. This indicates that there were no significant differences in the A content between these blends.

The content of fixed carbon (FC) decreased with the increasing proportion of the copra meal in the blends. However, as shown by the results of statistical analysis, significant changes were caused only after the addition of at least 40% copra meal (M60C40). Moreover, statistical analysis did not confirm significant differences in the FC content in the blends containing 30–60% copra meal (M70C30–M40C60).

The carbon (C) content was 46.43% in the copra meal and 48.45% in the miscanthus biomass and decreased with the increase in the copra meal content in the blend. Statistical analysis confirmed the significance of these changes. The 10% copra meal addition contributed to a significant reduction in C content. However, it is noteworthy that a further increase in the copra meal amount (up to 30%—M70C30) did not affect the C content significantly. Statistical analysis showed no significant differences in the C content in blends supplemented with 50–100% copra meal (M50C50–M0C100).

The hydrogen (H) content was 6.09% and 7.019% in the miscanthus biomass and copra meal, respectively. In the blends of these raw materials, it increased with the increase in the proportion of copra meal. Significant changes in the H content were noted after the addition of 10% copra meal (M90C10). The subsequent higher levels of the additive induced statistically significant changes in the H content. Statistical analysis showed that the H content did not differ significantly between the M90C10–M80C20, M70C30–M60C40, and M50C50–M40C60 blends.

The content of N in the miscanthus biomass was 0.24%. It is a typical content of these elements in biomass [9] and does not differ from the content in other energy crops. The content of N in the copra meal was 3.15%, which may be related to the 15–20% protein content [21]. As shown by statistical analysis, the addition of at least 10% copra meal significantly increased the content of this element. A further increase in the proportion of the additive in the blends resulted in significant differences in the nitrogen content (different homogeneous groups). A noteworthy finding is that the highest nitrogen content was detected in the copra meal M0C100 sample, i.e., it was over eight times higher than that in the M90C10 blend.

The sulfur (S) content in the analyzed biomass and blends was significantly different, i.e., 0.004% and 0.125% in the miscanthus biomass and copra meal, respectively. The high content of sulfur in the copra meal may be related to its content of sulfur amino acids [21]. The results of statistical analysis indicated that the increase in the copra meal amount in the blends by 10% (M90C10) and up to 40% (M60C40) resulted in a significant increase in the sulfur content. However, there were no significant differences in the sulfur content between blends M70C30 and M60C40. A further increase in the proportion of the copra meal resulted in significant changes in the sulfur content.

The higher heating value (HHV) and the lower heating value (LHV) of the basic raw materials were 19,606 kJ·kg<sup>-1</sup> and 18384 kJ·kg<sup>-1</sup>, respectively, for the copra meal and 17,578 kJ·kg<sup>-1</sup> and 16,307 kJ·kg<sup>-1</sup>, respectively, for the miscanthus biomass. The high value of the HHV for the copra meal is related to its fat content. These values increased with the addition of the copra meal. Statistical analysis confirmed the significance of these changes. A significant increase in these parameters was observed after the addition of 10% of the copra meal in the M90C100 blend (compared to miscanthus biomass M100C0). A further increase in the amount of the copra meal (up to 30% (M70C30)) did not exert a significant effect on the HHV or LHV. The results of statistical analysis also showed no significant differences between the mean HHV and the LHV in the M70C30 to M50C50 blends. Both values in the blend containing at least 60% of the copra meal (M40C60) were significantly higher than those in the M50C50 blend containing 50% or a lower proportion of this raw material.

Some studies have confirmed agri-food wastes rich in oily substances (e.g., industrial tomato residues) have a high level of the HHV [27]. Their energy parameters are considerably more favorable than those of wood waste, straw, and bark [28] or walnut husks [29], whose HHV ranges from 18,000 to 20,000 kJ·kg<sup>-1</sup>.

The fat content in the basic raw materials was 10.94% in the copra meal, whereas no fat was detected in the miscanthus biomass.

The most important criteria for the energy assessment of fuels and biofuels include LHV and the percentage of A and S content. Considering these criteria and the absence of significant differences between some of the blends, miscanthus biomass M100C0 and blends with 10%, 30%, and 50% copra meal, i.e., M90C10, M70C30, and M50C50, respectively, were further analyzed. The copra meal showed a high value of the LHV parameter. It was over 2000 kJ·kg<sup>-1</sup> higher than that of the miscanthus biomass, which made it an attractive addition to the process of the production of solid biofuels. The LHV of the M90C10–M70C30 blends did not differ significantly, as in the case of M60C40 and M50C50. The A content in some of the blends did not differ significantly. No significant differences in this parameter were found between the blends M90C10–M80C20, M70C30–M60C40, and M50C50–M40C60. The S content in the blends increased with the increasing content

of the copra meal, which was characterized by a high level of this element (0.226%); this clearly indicates the need to limit the amount of this additive in the production of solid biofuels. The M60C40 and M50C50 blends did not differ significantly in the content of this element. The S content in fuels is directly associated with subsequent emissions of sulfur oxides formed during fuel combustion to the atmosphere. Therefore, the content of this element should be limited and monitored in solid biofuels, as some types of biomass may contain a significant amount of S, as confirmed here.

There are literature reports on the use of rapeseed and sunflower pomace as well as residues from olive oil pressing as a raw material for the production of solid compacted biofuels [30–33]. The results obtained are fairly promising. As demonstrated by [31], rapeseed pomace is a good alternative to coal in terms of both sulfur content and LHV. However, for effective combustion, it is necessary to use appropriate combustion systems. Kobayashi et al. [32] showed the possibility of using sunflower pomace to replace other plant materials.

High fat content in plant raw materials may affect the pelleting process and the mechanical properties of the product. Oilseed pomace with fat content similar to that used in the present study was used successfully for pellet production by [31]. As reported by [34], an increase in the content of fatty raw materials in a densified mixture results in an increase in the compaction process efficiency on the one hand and reduction in the strength properties of pellets on the other hand.

### 3.2. Properties of Pellets

In the present study, the use of the M0C100 copra meal pellets as biofuel was not considered because of their low strength, low bulk density, and high S and A content. The findings of the analyses of the copra meal pellets are presented to show the differences not only in the results of the proximate and ultimate analysis and heating value estimation for the raw materials, but also in the energy and mechanical properties of pellets produced from these materials.

The results of the durability, bulk density, and density of pellets produced from the analyzed blends and the energy consumption in the densification process are presented in Table 2.

**Table 2.** Durability, bulk density, density of pellets, and energy consumption for pellets of various blends.

Parameter	M100C0	M0C100	M90C10	M70C30	M50C50
Durability [%]	91.4	87.2	97.2	95.1	89.1
	±1.0 <sup>b</sup>	±0.0 <sup>a</sup>	±0.6 <sup>d</sup>	±0.0 <sup>c</sup>	±0.6 <sup>ab</sup>
Bulk density [kg·m <sup>-3</sup> ]	567.3	255.1	514.9	417.4	298.9
	±6.7 <sup>e</sup>	±0.5 <sup>a</sup>	±3.4 <sup>d</sup>	±3.2 <sup>c</sup>	±0.5 <sup>b</sup>
Pellet density [kg·m <sup>-3</sup> ]	1375	1161	1334	1201	1184
	±10.7 <sup>e</sup>	±4.4 <sup>a</sup>	±2.5 <sup>d</sup>	±4.0 <sup>c</sup>	±3.8 <sup>b</sup>
Energy consumption [Wh·kg <sup>-1</sup> ]	114.33	24.11	84.45	63.42	39.09
	±1.53 <sup>e</sup>	±0.42 <sup>a</sup>	±1.20 <sup>d</sup>	±0.81 <sup>c</sup>	±1.01 <sup>b</sup>

±: Standard deviation; mean values with the same letter in a row are not significantly different at  $p < 0.05$  in Tukey's HSD test.

Durability is the most common parameter of the quality of stored and transported pellets. High pellet durability reduces potential problems in the fuel feed systems and limits dust emission during operation of the boiler. The lowest durability, i.e., 89.1% and 87.2%, was shown by pellets produced from the mixture of miscanthus biomass with the largest (50%) addition of copra meal (M50C50) and pellets made from copra meal alone (M0C100), respectively. The durability of the pellets significantly increased after the addition of 10% copra meal (97.2%) to the miscanthus biomass (M90C10), but a further increase in the amount of this additive in the blends did not have a positive effect on the durability of the pellets, especially for the M50C50 blend. Significant differences in the



durability of pellets produced from the different blends were found in all cases, except for the M50C50 and M0C100 pellets (the same homogeneous group). According to the European standards (EN 14961), the durability of pellets should be  $\geq 97.5\%$ . Although none of the tested blends exhibited such durability values, a significant improvement in this parameter was evident.

Similar problems related to miscanthus biomass pelleting and the durability of pellets were reported by [14] and [35]. Temmerman et al. [35] obtained miscanthus pellets with a strength of 90.5%. The durability of pellets produced from a mixture of miscanthus and wood sawdust in a 50:50 ratio was 98%. Moon et al. [14] obtained pellets with ultimate durability of 97.5% after the preliminary biomass densification and optimization of the pelleting process. Miscanthus pellets produced by [36] showed 95.3% durability. Recent reports [37] describe miscanthus pellets with 94.6% durability.

High pellet density affects both the combustion process and the transport conditions [28]. The miscanthus biomass alone (M100C0) pellets showed the highest density, i.e.,  $1375 \text{ kg}\cdot\text{m}^{-3}$ , whereas the copra meal alone (M0C100) pellets had the lowest value of this parameter, i.e.,  $1161 \text{ kg}\cdot\text{m}^{-3}$ . The density of pellets produced from the blends of these raw materials decreased with the increasing content of the copra meal. All the differences were statistically significant. Although the ISO standards do not specify pellet density as a quality parameter, it has been observed that the optimal value for high-quality pellets is  $>1200 \text{ kg}\cdot\text{m}^{-3}$ . Temmerman et al. [35] obtained miscanthus pellets with a density of  $1300 \text{ kg}\cdot\text{m}^{-3}$ . As reported by [28], the density of wood pellets was in the range from 1030 to  $1300 \text{ kg}\cdot\text{m}^{-3}$ . For soybean, pea, chamomile, birch sawdust, and their blends, Zawislak et al. obtained lower pellet density values ranging from 1030 to  $1150 \text{ kg}\cdot\text{m}^{-3}$  [38].

Bulk density is another important parameter of pellets determining their transport, handling, and storage efficiency. Higher bulk density contributes to higher pellet transport capacity and less storage space. This parameter is influenced by the specific pellet density. The highest bulk density value of  $567.3 \text{ kg}\cdot\text{m}^{-3}$  was found for the M100C0 miscanthus biomass pellets, whereas the lowest, i.e., an approximately twofold lower value ( $255.1 \text{ kg}\cdot\text{m}^{-3}$ ), was obtained for M0C100. The addition of the copra meal significantly decreased the bulk density of the pellets. Similar results for bulk density of miscanthus pellets were reported by [14] and [36], i.e.,  $624 \text{ kg}\cdot\text{m}^{-3}$  and  $615.2 \text{ kg}\cdot\text{m}^{-3}$ , respectively.

The addition of copra meal reduced the AC strength of the pellets (Table 3). Statistical analysis confirmed the significance of these changes. A noteworthy finding is that the addition of 10% copra meal significantly reduced the mechanical strength of the M90C10 pellets. This parameter in the pellets containing 50% copra meal (M50C50) was threefold lower than that in the miscanthus biomass pellets (M100C0). Similarly, other authors who investigated the effect of various additives on the mechanical strength of biomass pellets reported lower values of this parameter in additive-supplemented products [23,39]. A study conducted by [23] indicated a possibility of improving the AC strength of pellets by increasing the pressure level in the die. Rhén et al. found that a higher temperature during the granulation process has a greater impact on the mechanical strength of wood pellets [40].

**Table 3.** Results of the mechanical strength tests for pellets of various blends.

Parameter	M100C0	M0C100	M90C10	M70C30	M50C50
Axial compression, AC [MPa]	3.025	0.330	1.976	1.602	0.985
	$\pm 0.260^a$	$\pm 0.047^e$	$\pm 0.182^b$	$\pm 0.025^c$	$\pm 0.170^d$
Three-point compression, 3PC [MPa]	0.094	0.009	0.056	0.049	0.021
	$\pm 0.004^a$	$\pm 0.003^c$	$\pm 0.009^b$	$\pm 0.013^b$	$\pm 0.006^c$
Point compression, PC [MPa]	0.704	0.152	0.412	0.449	0.477
	$\pm 0.136^a$	$\pm 0.020^c$	$\pm 0.006^b$	$\pm 0.077^b$	$\pm 0.026^b$

±: Standard deviation; mean values with the same letter in a row are not significantly different at  $p < 0.05$  in Tukey's HSD test.

The strength of the material assessed in the 3PC test was significantly lower in the copra meal-containing pellets. However, statistical analysis did not confirm any significant differences between the mean strength of the M90C90 and M70C30 samples. The results of statistical analysis also suggest that the increase in the proportion of the copra meal from 50% to 100% did not exert a significant effect on changes in the strength of the pellets in the 3PC test. This indicates that other factors may have influenced the mechanical properties of the material. The authors of [32] showed a correlation between the initial moisture of the copra meal and the mechanical strength of pellets produced from this raw material. As recommended by Missagia et al., plant materials with initial moisture of approximately 10% should be moistened up to 20% before the pressing process [24]. For rice husk biomass, the highest strength in the PC test and the 3PC test was exhibited by pellets produced from the raw material with initial moisture content of 17%.

The highest PC strength was exhibited by the nonsupplemented pellets (M100C0) (Table 3). Significant changes in this parameter were observed in the M90C10 variant supplemented with 10% of the additive. As shown by statistical analysis, a further increase in the proportion of copra meal (up to 50%) did not cause significant changes in the mechanical strength of the material in the PC test (the pellet strength slightly increased). The results of the PC test were slightly different from the mean values obtained in the 3PC test. Higher dispersion of the values of this parameter was also observed. As suggested by [23], this may be related to the nonhomogeneity of the raw materials used. Narra et al. showed a possibility to significantly increase the biomass pellet strength in the PC and 3PC (breaking) tests by appropriate pretreatment of the raw material [39], regardless of the raw material used.

The miscanthus pelleting process (M100C0) showed the highest energy consumption value, i.e.,  $114.33 \text{ Wh}\cdot\text{kg}^{-1}$ , whereas the lowest value of this parameter was recorded for the copra meal (M0C100) pelleting process, i.e.,  $24.11 \text{ Wh}\cdot\text{kg}^{-1}$ , which represents only 21% of energy required for the miscanthus biomass densification process. The energy consumption in the process of densification of the blends decreased significantly with the increase in the proportion of copra meal added. The 10% copra meal content in the M90C10 blend contributed to a decrease in the energy consumption in the process to  $84.45 \text{ Wh}\cdot\text{kg}^{-1}$ , which indicated a significant reduction in the energy demand by slightly more than 26%. The increase in the copra meal proportion added to the blends resulted in a further decrease in the energy consumption in the pelleting process. The addition of 30% copra meal in the M70C30 pellet blend reduced the energy consumption in the process by approximately 44%, whereas the 50% copra meal addition in the M50C50 blend lowered this parameter by 65%. In the pelleting process, fat acts as a lubricant and lowers the friction between particles and between particles and the die wall in the pellet mill chamber. The high fat content in the copra meal (over 10%) noticeably reduced the energy consumption in the pelleting process. However, reduced friction in the die is also associated with lower pressure, which results in the production of pellets with lower durability. The addition of animal or vegetable fat (oil) to the pelleted material results in a lower durability of the product [41].

Fusi et al. [37] obtained miscanthus pellets with an energy consumption of  $204 \text{ Wh}\cdot\text{kg}^{-1}$  in produced pellets (with 94.6% durability), which seems to be quite a high energy consumption. In a study of energy consumption in the process of the densification of a blend of pine sawdust with food and forestry industry wastes (coffee dregs, cocoa shells, grape marc, fragments of pine cones), Garcia et al. [42] reported the value of this parameter in the range of  $80\text{--}250 \text{ Wh}\cdot\text{kg}^{-1}$ . The energy consumption value for pelleting corn cob waste [43] ranged from 80 to almost  $400 \text{ Wh}\cdot\text{kg}^{-1}$ . Similarly, in the present study, this process was not optimized, and the high values were accompanied by the low efficiency of the pelleting process. In their investigations, Zawislak et al. [38] determined the energy consumption in the process of pelleting chamomile waste ( $108 \text{ Wh}\cdot\text{kg}^{-1}$ ) and birch sawdust ( $100 \text{ Wh}\cdot\text{kg}^{-1}$ ). However, the supplementation of these materials with fat-containing pea and soybean waste contributed to a reduction in energy consumption to  $38.4\text{--}44.7 \text{ Wh}\cdot\text{kg}^{-1}$  [38].

### 3.3. Bioenergy Indicators

To determine the energy benefits of the pellets, the energy yield was assessed considering the energy inputs incurred for pellet production by using Equation (2):

$$EY = LHV - ECU, \quad (2)$$

where:

EY—Energy yield of pellets [ $\text{Wh}\cdot\text{kg}^{-1}$ ],

LHV—Lower heating value [ $\text{Wh}\cdot\text{kg}^{-1}$ ],

ECU—Energy consumption unit [ $\text{Wh}\cdot\text{kg}^{-1}$ ].

Additionally, the energy efficiency was determined as (initial energy content in the biomass—energy loss during pelleting)/(initial energy content in biomass) by using Equation (3):

$$EE = \frac{IE - ECU}{IE} \cdot 100\%, \quad (3)$$

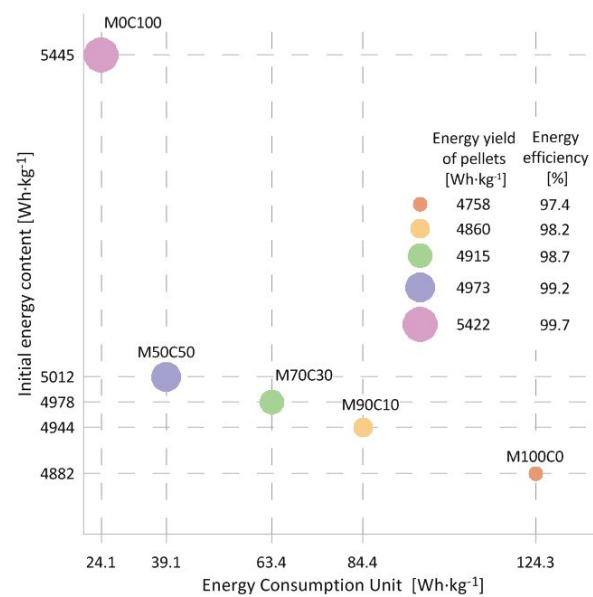
where:

EE—Energy efficiency [%],

IE—Initial energy content of biomass [ $\text{Wh}\cdot\text{kg}^{-1}$ ],

ECU—Energy consumption unit [ $\text{Wh}\cdot\text{kg}^{-1}$ ].

Figure 3 presents the relationship between the Initial Energy Content (IE) and Unit Energy Consumption (UEC) versus the values of Energy Yield and Energy Efficiency of Pellets (EY and EE).



**Figure 3.** Energy yield and energy efficiency of pellets (EY and EE) vs. the relationships between initial energy content and unit energy consumption (IE and UEC). Individual bubbles are assigned both the EE and EY values as shown in the legend.

The M100C0 biomass pellets exhibited the lowest EY of  $4758 \text{ Wh}\cdot\text{kg}^{-1}$ . This is related to both the low LHV value and the high energy input during the pelleting process. Consequently, the EE was also low, i.e., 97.4%. The addition of the copra meal improved the energetic properties of the pellets through the reduction of energy consumption in the pelleting process and the high LHV value. The 10% proportion of the copra meal in the blend was sufficient to increase the EY by  $102 \text{ Wh}\cdot\text{kg}^{-1}$ , while the EE increased to 98.2%. Furthermore, with 30% copra meal supplementation, the EY was  $4915 \text{ Wh}\cdot\text{kg}^{-1}$ , and the EE increased to 98.7%. The highest EY value of  $5422 \text{ Wh}\cdot\text{kg}^{-1}$  and EE of 99.7% were recorded

for the copra meal pellets; however, as mentioned earlier, these pellets were not considered as the target biofuel.

The energy density (ED) of pellets is important in transport and storage processes. An increase in ED is accompanied by reduction in the space required for storage and transport, which enhances the efficiency and lowers the cost of pellets for both the pellet producer and the end user [28]. The volumetric ED was calculated from the measured LHV value and bulk density DB of the pellets in accordance with Equation (4):

$$ED = DB \cdot LHV, \quad (4)$$

where:

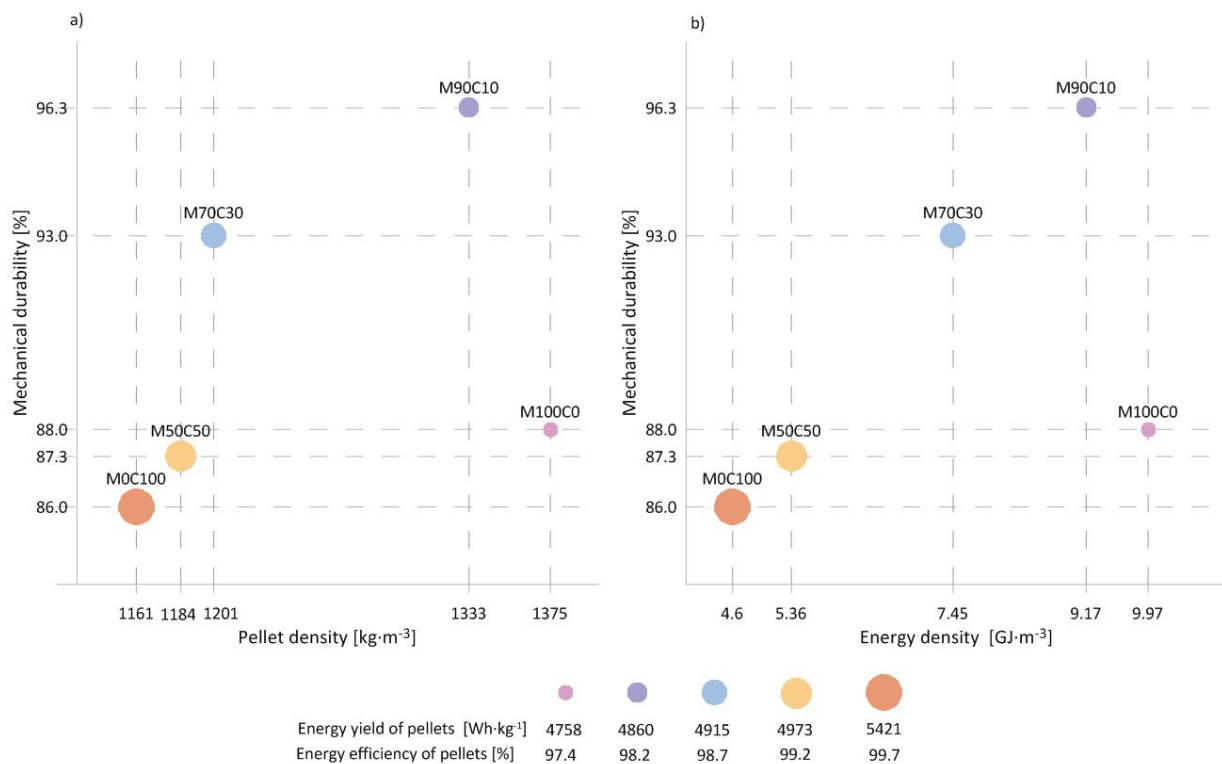
ED—Energy density [ $\text{GJ} \cdot \text{m}^{-3}$ ],

LHV—Lower heating value [ $\text{GJ} \cdot \text{kg}^{-1}$ ],

DB—Bulk density [ $\text{kg} \cdot \text{m}^{-3}$ ].

The ED of the pellets ranged from 4.6 to  $9.97 \text{ GJ} \cdot \text{m}^{-3}$  (Figure 4b). Despite the low LHV value, the high bulk density of the M100C0 miscanthus pellets ensured the highest ED. Simultaneously, the low bulk density of the M0C100 copra meal pellets resulted in their lowest ED despite the highest LHV value. Therefore, the addition of copra meal to the biomass has an evident effect on the ED of the analyzed pellets. The results obtained by other authors may differ, as different methods were used to determine the ED. A methodology similar to that employed in the present study was used by Garcia et al. [42]. The authors reported higher values of ED in the range of  $7.7\text{--}12.0 \text{ GJ} \cdot \text{m}^{-3}$ , which was associated with the use of wood waste mixed with agri-food industry waste as raw materials for the production of pellets.

Figure 4 presents the relationship between the initial energy content and unit energy consumption (EC) (IE and UEC, respectively) versus the values of energy yield and energy efficiency of pellets (EY and EE, respectively).



**Figure 4.** Energy efficiency (EE) and energy yield (EY) of pellets vs. mechanical durability: (a) pellet density and (b) energy density. Individual bubbles are assigned both the EE and EY values as shown in the legend.

The results of the assessment of the quality parameters of the pellets related to the processes of storage, distribution, and use in boilers were analyzed in terms of their energy acquisition costs (Figure 4a,b). To this end, the results of mechanical durability and pellet density (Figure 4a) and ED (Figure 4b) tests were compared with EE and EY. In terms of the logistics of pellet distribution to the recipient, the copra meal pellets proved to be the least attractive product; although they exhibited 99.7% EE, their ED was low ( $4.6 \text{ GJ}\cdot\text{m}^{-3}$ ), which combined with their low mechanical durability can increase the distribution cost and lead to a high risk of crumbling-related losses during transport. As mentioned above, these pellets were not considered in terms of their suitability to serve as biofuel. On the other hand, the miscanthus biomass pellets showed the highest ED ( $9.97 \text{ GJ}\cdot\text{m}^{-3}$ ) and pellet density, which definitely facilitate transport processes. However, their low mechanical durability (91.4%) and the lowest EE (97.4%) decrease the suitability of this product for heating applications.

In the analysis of pellet durability and ED reflected in the energy consumption in the production process (Figure 4b), it was evident that the most favorable strength and energy parameters were exhibited by pellets from miscanthus biomass supplemented with 10% and 30% of the copra meal (M90C10 and M70C30, respectively), and energy consumption related to the production of these pellets was lower than that for the densification of miscanthus biomass alone without the copra meal additive (M100C0). These pellets exhibited over 95% durability, and the energy demand in the production process was reduced by 26% and 44%, respectively. The most favorable energy and strength parameters were determined for the M90C10 pellets (with 10% copra meal), while lower energy consumption was noted for the densification of the M70C30 blend (with 30% copra meal).

The analysis of the effect of copra meal addition to miscanthus biomass on the pelleting process revealed that although the increase in the additive dose had a positive effect on EE, the other properties of the pellets, i.e., density and durability, were worsened. The 50% addition of copra meal (M50C50) contributed to an increase in EE to 99.2% accompanied by a significant decrease in the values of mechanical durability (89.1%), pellet density ( $1184 \text{ kg}\cdot\text{m}^{-3}$ ), and ED ( $5.36 \text{ GJ}\cdot\text{m}^{-3}$ ) (Figure 4a,b). Such low values of operational parameters exclude these pellets from use.

The most favorable parameters in terms of the operation in fuel feed and distribution systems were obtained for pellets from blends supplemented with 10% copra meal (M90C10), which had the highest mechanical durability (97.2%) but slightly lower pellet density ( $1333 \text{ kg}\cdot\text{m}^{-3}$ ) and ED ( $9.17 \text{ GJ}\cdot\text{m}^{-3}$ ) than those determined for the miscanthus biomass pellets (M100C0). There was also a slight increase in EE (98.2%). Therefore, the analysis of the results shown in Figure 4a,b allows us to conclude that the addition of 10–30% copra meal has a positive effect on the performance parameters and energy properties of pellets, reduces energy consumption in the pelleting process, and increases EE and EY.

#### 4. Conclusions

The present study assessed the possibility of using copra meal waste as an additive in the production of pellets from miscanthus biomass.

The proximate and ultimate analysis of the raw materials and their blends facilitated selection of those with promising energy parameters. Blends with 10%, 30%, and 50% copra meal were selected for use in the pressure agglomeration process. The analyses of the densification process and the pellets showed that the addition of copra meal to miscanthus biomass was an effective approach to improve the process and properties of the product. When the copra meal addition did not exceed 30%, the pellets exhibited over 95% durability, over  $1200 \text{ kg}\cdot\text{m}^{-3}$  density, and over  $417 \text{ kg}\cdot\text{m}^{-3}$  bulk density. The pellets did not meet all the requirements of the standards established for domestic and industrial use (EN 14961). Nevertheless, given the 44% reduction in energy consumption and the EE of  $4815 \text{ Wh}\cdot\text{kg}^{-1}$ , this additive may be an interesting material for the production of pellets from various types of biomass.

The tests performed in the study facilitated the production of pellets that mostly met the quality standard requirements. The research results prove that it is possible to significantly reduce energy consumption in the miscanthus biomass pelleting process by adding copra meal waste as a biocomponent. The addition of copra meal in the range of 10–30% is recommended.

#### *Research Limitations and Suggestions for Future Research*

When analyzing the obtained results, it should be borne in mind that the copra meal properties may differ depending on the batch, as they may be influenced by three main factors: the extraction process, storage conditions, and the drying process [21].

The pelleting process itself was not optimized in terms of process parameters. However, the results of the present study prove the possibility of obtaining pellets with high utility and energy parameters and indicate the need for further research. This will enable us to optimize the parameters of the compaction process so as to obtain high-quality pellets at low energy inputs.

The present study investigated the addition of copra meal to one raw material, i.e., miscanthus biomass. The results suggest that, because of its fat content, copra meal can be successfully used as an additive for the densification of other biomass materials requiring high energy consumption in the pelleting process.

**Author Contributions:** Conceptualization, D.A., G.Z. and J.S.-B.; methodology, G.Z., A.B.-K. and S.O.; validation, T.S., J.S.-B. and A.B.-K.; formal analysis, A.B.-K.; investigation, T.S., J.S.-B. and B.Z.; resources, G.Z., A.B.-K. and B.Z.; data curation, G.Z.; writing—original draft preparation, J.S.-B., G.Z. and A.B.-K.; writing—review and editing, T.S., D.A. and S.O.; visualization, G.Z.; supervision, T.S. and D.A.; project administration, G.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** The APC was funded from the ‘Excellent science’ program of the Ministry of Science and Higher Education as a part of the contract no. DNK/SP/465641/2020 “The role of the agricultural engineering and environmental engineering in the sustainable agriculture development”. The research was funded by appropriations of the Faculty of Production Engineering, University of Life Sciences in Lublin within the framework of grants to maintain the research potential.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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