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IMPACT OF MOISTURE AND SPEED OF THRESHERS ON EFFICIENCY OF CRUSHING OF LUPINE SEEDS

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ABSTRACT

The objective of the paper was to determine the impact of moisture and rotational speed of threshers on the process of crushing of lupine seeds. Raw material was led to four levels of moisture from 8 to 14% every 2%. The studies were carried out on the laboratory hammer mill with the use of variable speeds of mill hammers within 5500-7000 rot·min^{-1}. The studies that were carried out proved significant relations ($p<0.05$) between the analysed process variables and energy consumption and susceptibility of seeds to crushing. It was stated that along with the increase of the rotational speed, a reduction in the drop of the average dimension of particles of mill takes place. Along with the increase of moisture of lupine from 8 to 14% a unit energy of crushing increases on average by approx. 83%. It was proved that the susceptibility ratio of seeds to crushing increases along with the increase of raw material moisture. Such relations were determined for all investigated rotational speeds of hammers.

List of markings:

- d_m – average size of particles, (mm)
- E_f – rate of seeds susceptibility to crushing, (J·m^{-2})
- E_r – unit energy consumption of crushing^{-1}, (J·g^{-1})
- E_{roz} – total energy of crushing, (J)
- h_i – average value of the class range, (mm)
- m_r – mass of the crushed sample, (g)

m_o – initial mass of raw material, (g)
m_1 – mass of raw material after drying, (g)
n – amount of the applied sieves,
P_i – participation of particles that stayed on a given sieve, (%)
S_n – surface area of particles after crushing, (m^2)
w_0 – initial moisture of raw material, (%)
m_1 – moisture of raw material after drying, (%)

Introduction

Lupine seeds due to health and nutritive values may be used both in the human and livestock diet. "Sweet" lupine in this context is of particular meaning, considerably devoid of alkaloids which cause that seeds are untasty and sometimes even toxic. Some lupine cultivars subjected to a suitable treatment give products with properties that are remarkably similar to soya products, especially if it is related to composition and assimilability (Olkowski, 2018).

Another significant argument for the use of lupine as a crop is its natural ability to leave substantial quantities of nitrogen compounds in soil, which influences consumption of mineral fertilizers. Moreover, lupine plays a significant role due to the ability to release limited phosphorus, unavailable for other plant species which simultaneously guarantees better conditions for successive plants growth, mainly grains (Roszak, 1999; Ma et al., 2019).

Lupine is perceived as a precious functional element of grain, fruit, dairy and meat products (Bartkiene et al., 2016). Its addition may result in both supplementation of grain protein with deficient lysine as well as introduction of oligosaccharides - compounds that are significant in counteracting diseases of a digestive system (Cruz-Chamorro et al, 2019). It is also used as an additive to bread, which causes the increase of the product shelf life and raises water absorption volume of bread and shortens time of the dough growth (Wandersleben et al., 2018). Moreover, proteins which occur in lupine seeds have properties that reduce the level of cholesterol in the system (López and Goldner, 2015).

In animal feeding, lupine may be a valuable source of protein in fodders for pigs, ruminants, and poultry (Volek et al., 2018; Zduńczyk et al., 2019). For some age groups of animals its admissible content may reach as much as 15% of weight constituting thus a precious substitute of soya meal (Grudniewska, 1998; Lamp et al., 2015). A technological process of fodder production with its use requires many treatments such as hulling, conditioning and fragmentation (Grochowicz and Andrejko, 1998; Andrejko and Grochowicz, 1999).

Efficiency of production processes in an agri-food industry considerably depends on its proper fragmentation of processed raw material (Kulig and Laskowski, 2002). Crushing is required both due to the increase of the digestion rate as well as to the proper course of technological processes of their refinement (Ball et al., 2015; Gimenoa et al., 2015). It is known that crushing of plant raw materials is related to high energy inputs (Laskowski and Łysiak, 1999; Laskowski et al., 2005; Mayer-Laigle et al., 2018a). In case of granular materials, this process is the most often carried out with the use of hammer mills (Mayer-Laigle et al., 2018b).

Taking the above into consideration, the aim of this paper is to investigate the impact of the moisture degree and rotational speed of mills on the course of the sweet lupine seed crushing. These factors (next to a diameter of openings on hammer sieves) mainly decide on the course of the process and degree of crushing and incurred energy inputs.

Materials and Methods

Th studies on the crushing process were performed on the laboratory hammer mill POLYMIX -Micro - Hammermill MFC. The hammer mill cooperated directly with a computer measuring system of active power single phase. Particular characteristics of the measurement stand were presented in the paper by Laskowski and Łysiak (1999).

A research material consisted of narrow leaf lupine of *Kurant* cultivar. Raw material was dried according to PN-91/A-74010 to obtain a complex degree of moisture i.e. 8,10,12 and 14% (±0.2 %). Required moisture of raw material was determined based on the pattern on the variability of mass in time, according to the following relation (Pabis et al., 1998):

$$m_1 = m_0\left(\frac{100-w_0}{100-w_1}\right) \quad \text{(g)} \tag{1}$$

Then, the prepared seeds were subjected to crushing with the use of a sieve with a diameter of opening of 2mm. During the process, four values of hammer mill speed were applied i.e. 5500, 6000, 6500 and 7000 rot·min^{-1}. The measurements were made in five iterations for each speed and seed moisture.

For crushed samples of lupine seeds a size distribution composition was determined according to the Polish standard (PN-89/R-64798) which allowed determination of an average size of particles according to the formula (Branland, 1997):

$$d_m = \frac{\sum_{i=1}^{n} h_i P_i}{100} \quad \text{(mm)} \tag{2}$$

Unit energy inputs of crushing E_r were determined from the formula:

$$E_r = \frac{E_{roz}}{m_r} \quad (\text{J}\cdot\text{g}^{-1}) \tag{3}$$

On the other hand, the index of susceptibility to crushing E_f was determined as a ratio of the total energy collected during crushing and surface of particles after crushing (Posner 1991):

$$E_f = \frac{E_{roz}}{S_n} \quad (\text{J}\cdot\text{m}^{-2}) \tag{4}$$

Measurement results were subjected to statistical analysis with the use of STATISTICA program. The analysis covered determination of mean values, errors, and standard deviations. Moreover, a single analysis of variance was carried out and the significance of differences between the mean values was determined with the use of Tulkey's test. It guarantees, to a considerable extent, maintenance of an error of I type and the assumed level of significance when many simultaneous comparisons are carried out. Moreover, relations in the form of regression equations were determined. All statistical analyses were made with an assumed level of significance of $\alpha = 0.05$.

Results and Discussion

The obtained research results proved that both moisture as well as speed of hammer mills significantly affect the parameters of the process of crushing of lupine seeds. In table 1-3 results of analysis of variance were presented while in table 4 regression equations that describe the obtained relations. Statistical analysis proved significant differences in values of the average size of particles d_m (tab. 1).

Table 1.
Analysis of variance for mean size of particles d_m (mm)

Parameters of analysis of variance	Hammers speed (rot·min^{-1})	SS · 10^4	df	MS · 10^4	F-4	p
Absolute term		0.06	1	0.06	2.31	0.000
Moisture	7000	0.00	3	0.00	0.00	0.009
Standard error		0.00	16	0.00		
Absolute term		0.07	1	0.07	2.66	0.000
Moisture	6500	0.00	3	0.00	0.00	0.001
Standard error		0.00	16	0.00		
Absolute term		0.06	1	0.06	2.20	0.000
Moisture	6000	0.00	2	0.00	0.00	0.033
Standard error		0.00	12	0.00		
Absolute term		0.04	1	0.04	1.61	0.000
Moisture	5500	0.00	1	0.00	0.00	0.017
Standard error		0.00	8	0.00		

When this parameter is analysed it should be emphasised that it more depends on the speed of hammers than on the moisture of raw material. The increase of hammers speed caused reduction of the parameter d_m value. Such relations were found referred to all investigated moisture of raw material. It may prove a prevailing role of technical and technological parameters of a hammer mill in shaping the grain size distribution composition of the raw material after crushing which was also proved by Kalwaj (2010) and Bochat and Zastempowski (2019). The value of the mean size of particles was presented in figure 1.

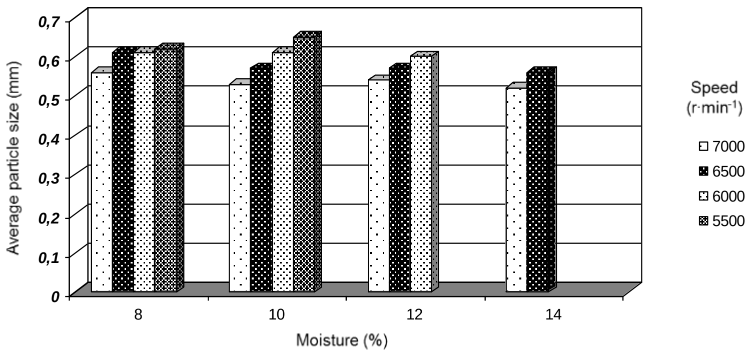

Figure 1. Mean size of particles d_m for particular moisture of lupine seeds and speed of hammer mills

For the set conditions of research (application of a sieve with a diameter of openings of 2mm), in case of raw material with the moisture of 12% and the use of speed of 5500 rot.·min^{-1} we were not able to carry out an impact decohesion. The same situation occurred also for a raw material with the moisture of 14% and the use of speed of 5500 and 6000 rot·min^{-1}. In all these cases material was not sieved through sieve meshes. Moreover, an attempt was made to crush lupine seeds with the moisture of 16%. However, for such moisture, the crushing process did not take place at any assumed value of the hammers speed.

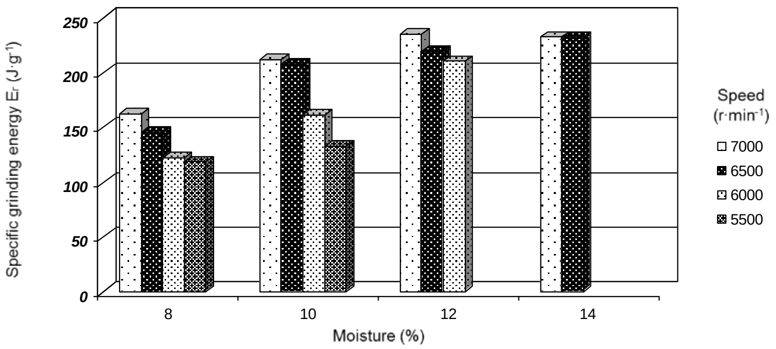

Figure 2. Unit energy of crushing E for particular moisture of lupine seeds and speed of hammer mills

Table 2.
Analysis of variance for unit inputs of energy for crushing E_r (J·g^{-1})

Parameters of analysis of variance	Hammers speed (rot·min^{-1})	SS	df	MS	F · 10^2	p
Absolute term		3.42	1	3.42	800.74	0.000
Moisture	7000	0.06	3	0.02	4.35	0.000
Standard error		0.00	16	0.00		
Absolute term		2.82	1	2.82	1481.11	0.000
Moisture	6500	0.10	3	0.03	17.50	0.000
Standard error		0.00	16	0.00		
Absolute term		2.13	1	2.13	677.49	0.000
Moisture	6000	0.14	2	0.07	21.84	0.000
Standard error		0.00	12	0.00		
Absolute term		0.63	1	0.63	440.61	0.000
Moisture	5500	0.00	1	0.00	1.47	0.000
Standard error		0.00	8	0.00		

The unit energy of crushing of lupine seeds with a varied moisture was from 118,706 J·g^{-1} (for the lowest rotational speed) to 234,842 J·g^{-1} (for the highest speed of hammers). The obtained results were presented in figure 2. Whereas in table 2 results obtained from the analysis of significance between the average values of parameter E_r were presented. The value of the parameter increased along with the increase of seed moisture and hammers' speed. A similar trend of energy consumption changes were proved also by other researchers on the example of grain seeds crushing (Dziki, 2008, Marks, 2010).

Also in case of the seed susceptibility rate to crushing, a single dimensional test of significance of variance proved that there are significant differences in the mean values of this parameter both referred to changes in seed moisture as well as hammers; speed (table 3). When analysing the value of E_f rate, it was observed that the increase of moisture caused the increase of this parameter. The highest value of the susceptibility ratio to crushing was proved at the moisture of 14% and speed of 6500 rot·min^{-1}, (14.50 kJ·m^{-2}). Whereas the lowest value (2.14 kJ·m^{-2}) was obtained at the speed of 5500 rot·min^{-1} and moisture of 8%. Figure 3 presents the relations between the susceptibility ratio and moisture for four values of rotational speed.

Table 3.
Analysis of variance for susceptibility index of seeds to crushing E_f (J·m^{-2})

Parameters of analysis of variance	Hammers speed (rot·min^{-1})	SS · 10^2	df	MS · 10^2	F · 10^2	p
Absolute term		35.84	1	35.83	30.86	0.000
Moisture	7000	0.40	3	0.13	0.11	0.000
Standard error		0.19	16	0.01		
Absolute term		33.92	1	33.92	28.79	0.000
Moisture	6500	0.09	3	0.05	0.26	0.000
Standard error		0.01	16	0.01		
Absolute term		15.61	1	15.61	22.33	0.000
Moisture	6000	1.97	2	0.99	1.41	0.000
Standard error		0.08	12	0.01		
Absolute term	5500	9.36	1	9.36	15.10	0.000
Moisture		0.06	1	0.06	0.10	0.013

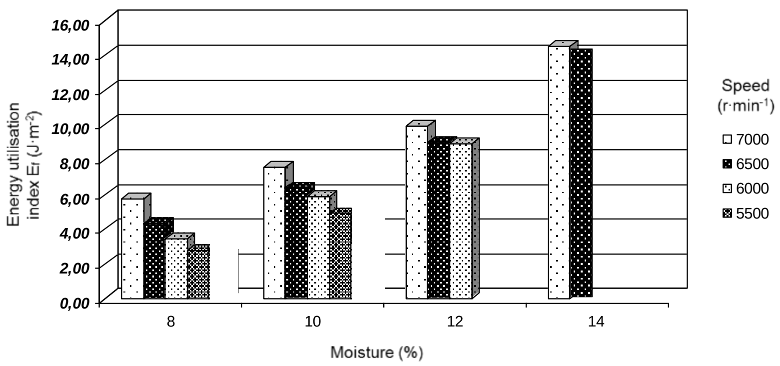

Figure 3. Ration of seeds susceptibility to crushing for particular moisture of lupine seeds and hammers speed

Regression equations that describe the relation of the investigated parameters of the process to moisture of raw material and rotational speed of hammers were set in table 4. The obtained data show that the obtained relations may be described with linear and square models. The determined values of R^2 coefficient show that the moisture of lupine explains over 94% of variability within the energy consumption of the crushing process. This happens in case of all investigated rotational speeds of hammers. Whereas the value of E_f index is explained on average in 70% with a variability of raw material moisture.

Table 4.
List of regression equations and value of determination ratio that determine the relation between the parameters of the process of crushing of lupine for various hammer speeds

Investigated property	Hammer speed (rot.min^{-1})	Equation	R^2
Unit energy inputs on crushing E_r (J·g^{-1})		$E_r = -2.279\ w_z^2 + 60.98\ w_z - 176.7$	0.948
Index of susceptibility of seeds to crushing E_f (J·m^{-1})		$E_f = 0.574\ w_z + 7.067$	0.564
Unit energy inputs on crushing E_r (J·g^{-1})	6500	$E_r = 0.702\ w_z^2 + 99.10$	0.960
Index of susceptibility of seeds to crushing E_f (J·m^{-1})		$E_f = 0.041\ w_z^2 + 7.766$	0.768
Unit energy inputs on crushing E_r (J·g^{-1})	6000	$E_r = -7.274\ w_z^2 + 173.5\ w_z - 800.2$	0.997
Index of susceptibility of seeds to crushing E_f (J·m^{-1})		$E_f = -0.568\ w_z^2 + 13.36\ w_z - 61.54$	0.907
Unit energy inputs on crushing E_r (J·g^{-1})	5500	$E_r = 7.280\ w_z + 60.46$	0.948
Index of susceptibility of seeds to crushing E_f (J·m^{-1})		$E_f = 0.791\ w_z + 2.550$	0.558

Conclusions

Based on the research results one may formulate the following conclusions:

1. Moisture of lupine seeds more influences the process of impact crushing than the change of the rotational speed of hammer mills.
2. It was stated that along with the increase of the rotational speed, a reduction in the drop of the average dimension of particles of mill takes place.
3. Along with the increase of moisture of lupine from 8 to 14% a unit energy of crushing increases on average by approx. 83%.
4. It was proved that the susceptibility ratio of seeds to crushing increases along with the increase of raw material moisture. Such relations were determined for all investigated rotational speeds of hammers.

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WPŁYW WILGOTNOŚCI I PRĘDKOŚCI BIJAKÓW NA EFEKTYWNOŚĆ ROZDRABNIANIA NASION ŁUBINU

Streszczenie. Celem pracy było określenie oddziaływania wilgotności i prędkości obrotowej bijaków na proces rozdrabniania nasion łubinu. Surowiec doprowadzano do czterech poziomów wilgotności od 8 do 14% co 2%. Badania przeprowadzono na laboratoryjnym rozdrabniaczu bijakowym, przy zastosowaniu zmiennych prędkość bijaków rozdrabniacza w przedziale 5500-7000 obr·min^{-1}. Przeprowadzone badania wykazały, że występują istotne zależności ($p<0,05$) pomiędzy analizowanymi zmiennymi procesu a energochłonnością i podatnością nasion na rozdrabnianie.

Słowa kluczowe: łubin, rozdrabnianie, wilgotność, prędkość bijaków, rozdrabniacz bijakowy