CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Engineering

Department of Mechanical Engineering

BACHELOR THESIS ASSIGNMENT

Rachid Mahroum

Evaluation of compression behaviour of bulk rapeseeds in linear pressing

Supervisor

Ing. Abraham Kabutey, Ph.D.

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Agricultural Engineering
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Thesis title

Evaluation of compression behaviour of bulk rapeseeds in linear pressing

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Objectives of thesis

(i) To describe the force-deformation curve characteristic of bulk rapeseeds at different forces, speeds and bulk seeds moisture content.
(ii) To determine the response surface regression models for describing the deformation energy, percentage oil yield and oil expression efficiency of bulk rapeseeds in relation to forces, speeds and moisture content.
(iii) To determine the optimal speed, force and moisture content of deformation energy, percentage oil yield and oil expression efficiency of bulk rapeseeds.
(iv) To discuss the effects of compression factors on oil yield and energy requirement of bulk rapeseeds in non-linear pressing involving mechanical screw presses.

Methodology

The experiment for achieving the objectives (i) and (ii) will be conducted at the laboratory of the Mechanical Department of Faculty of Engineering. A universal compression testing machine (ZDM 50, Czech Republic) and a pressing vessel diameter of 60 mm with a plunger will be used for the compression test by applying the Box-Behnken Design. The initial pressing height of the bulk rapeseeds will be measured at 60 mm. The forces and speeds will range from 60, 80 and 100 kN and 5, 10 and 15 mm/min respectively. The varying moisture content of the bulk rapeseeds will be determined using the moisture conditioning equipment Memmert GmbH+Co.KG. The data will be analysed statistically using the SPSS Software or STATISTICA software. Objective (iv) will be achieved through literature information.

The proposed extent of the thesis

60–70 pages

Keywords

Bulk rapeseeds, linear compression, non-linear compression, mechanical properties, regression models

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Recommended information sources

Demirel C, Kabutey A, Herak D, Gurdil G.A.K. 2017. Numerical estimation of deformation energy of selected bulk oilseeds in compression loading. IOP Conference Series: Materials Science and Engineering, 237(1), 1–5.

Divišová, M., Herák, D., Kabutey, A., Sigalingging, R., Svatoňová, T. 2014. Deformation curve characteristics of rapeseeds and sunflower seeds under compression loading. Scientia Agriculturae Bohemica, 45(3):180-186.

Ivanova, T., Kabutey, A., Herak, D., Cimen, D. 2018. Estimation of energy requirement of Jatropha curcas L. Seedcake briquettes under compression loading. Energies, 11(8), en11081980.

Kabutey, A., Herak, D., Mizera, C., Hrabe, P. 2018. Compressive loading experiment of non-roasted bulk oil palm kernels at varying pressing factors. International Agrophysics, 32(3), 357-363.

Kabutey, A., Herak, D., Mizera, C., Hrabe, P. 2018. Mathematical description of loading curves and deformation energy of bulk oil palm kernels. Agronomy Research, 16(4), 1687-1697.

Mizera, C., Herak, D., Hrabe, P., Kabutey, A. 2018. Extraction of oil from rapeseed using duo screw press. Agronomy Research, 16(Special Issue 1), 1118-1123.

Shkelqim Karaj & Joachim Müller (2019): Temperature influence on chemical properties of Jatropha curcas L. oil extracted with mechanical screw press, Biofuels, DOI: 10.1080/17597269.2018.1554946

Sigalingging, R., Sumono, Herak, D., Kabutey, A., Sigalingging, C. 2018. Influence of porosity, permeability and expression force on oil yield of jatropha seeds. Scientia Agriculturae Bohemica, 50(1), 56-62.

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ABSTRACT

This Thesis investigated the compression behaviour of bulk rapeseeds under compression loading by applying the response surface methodology using Box Behnken design (BBD) for three processing factors namely force: 60-100 kN, speed: 5-15 mm min^{-1} and moisture content: 5-11% (w.b.). The pressing vessel diameter of 60 mm and pressing height of the sample of 60 mm were considered. In total 17 experiments were conducted where oil yield (%), oil expression efficiency (%) and deformation energy (J) were calculated. The values of deformation (mm) were obtained directly from the compression tests. Based on the response surface regression results, the optimum processing conditions for oil yield and oil expression efficiency were observed at a force of 100 kN, speed of 5 mm min^{-1} and moisture content of 5% w.b. For energy, the optimum factors were found at forces of 90 and 96 kN, speeds of 5 and 6.5 mm min^{-1} and moisture content of 5% (w.b.). However, based on the compression test results, the optimum factors were achieved at force 80 kN, speed of 5 mm min^{-1} and moisture content of 5% (w.b.). Regression models were described for the responses: oil yield, oil expression efficiency and energy respectively. The coefficients of the regression models were statistically significant ($P < 0.05$). The effects of processing factors on oil yield and energy requirement of bulk rapeseeds in non-linear pressing involving mechanical screw presses were discussed. Validation of the predicted responses based on the optimized processing factors should be considered in future research.

KEYWORDS:

Rape oil-bearing crop, response surface methodology, Box Behnken design, mechanical properties, deformation curve patterns, uniaxial compression

DECLARATION

I hereby declare that this thesis is the result of my work and that it has not been submitted to this University or any institution for a degree. However, all references used in the development of the work have been acknowledged in the text and list of references.

In Prague	Date:
Rachid Mahroum	27.5.2020

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1 INTRODUCTION

1.1 Background

Global production of oilseed rape (*Brassica napus* L.) has substantially increased over the past decades (Carre and Pouzet, 2014; Fetzer, Herfellner, Stabler, Menner and Eisner, 2018; Zhang et al., 2020). The oil from rape is mainly used in human nutrition and biofuel production (Kasprzak et al., 2017). Rapeseed meal, a by-product of oil extraction is often used for animal feed or agricultural fertilizer while the protein in the cold-pressed meal between 35 and 40% can be used for the development of high value-added products (Zhang, Liu and Piao, 2012; Fetzer, Herfellner, Stabler, Menner and Eisner, 2018; Baker and Charlton, 2020; Zhang et al., 2020).

Several attempts have been made in the past, and are still considered to improve the oil extraction efficiency of mechanical screw pressing of oilseeds. According to Ohlson (1992), as cited in Singh and Bargale, (2000), most of the studies focused on the optimization of process variables such as applied pressure, pressing temperature and moisture conditioning of the oil-bearing material. Various pretreatments methods including physical (dehulling, cracking, size reduction), thermal (preheating, dry extrusion), hydrothermal (hot water soaking, steaming, blanching, flaking) and chemical (enzymatic hydrolysis) have been considered (Tindale and Hass, 1976; Bredeson, 1983; Khan and Hanna, 1983; Nelson, Wijeratne, Yeh, Wei and Wei, 1987; Ohlson, 1992; Williams, 1995; Bargale, Ford, Sosulski, Wulfson and Irudayaraj, 1999). These efforts according to Singh and Bargale (2000) have positively increased oil recovery efficiency for different oilseeds from 50% to 80%. However, the problem of the excessive number of oil extraction or passes remains resulting in increased specific energy consumption and wear and tear of equipment. Choking and jamming of the screw press are also encountered leading to excessive heating and burning of the cake and oil and thus loss of quality, energy and labour.

For the design and construction of equipment and structures for handling, transportation, processing and storage associated with oil extraction (Sirisomboon and Kitchaiya, 2009; Gupta and Das, 2000), it is important to understand the physical and mechanical properties of oilseeds such as rapeseeds. This Thesis investigated the mechanical properties and deformation curve characteristics of rapeseeds under compression loading by applying the response surface methodology using Box Behnken design (BBD) for three processing factors including force, speed and moisture content.

1.2 Objectives

For this study, the objectives were to:

(i) describe the force-deformation curve characteristics of bulk rapeseeds at different forces, speeds and bulk seeds moisture content.

(ii) determine the response surface regression models for describing the deformation energy, percentage oil yield and oil expression efficiency of bulk rapeseeds in relation to forces, speeds and moisture content.

(iii) determine the optimal speed, force and moisture content of deformation energy, percentage oil yield and oil expression efficiency of bulk rapeseeds.

(iv) discuss the effects of compression factors on oil yield and energy requirement of bulk rapeseeds in non-linear pressing involving mechanical screw presses.

2 LITERATURE REVIEW

2.1 Overview of oilseeds

As cited in Arrutia, Binner, Williams and Waldron, (2020), oilseeds provide the largest source of vegetable oil, and the residue after extraction is rich in protein. As a staple food, oilseeds provide many nutritious and functional components for human health such as starch, crude protein, oil content, fatty acid, amino acids, vitamins, phytosterols and polyphenols (Vithu and Moses, 2016; Yang et al., 2018). Oilseed production and consumption are significant worldwide and the quality and safety of oilseeds are important to human health (Arrutia, Binner, Williams and Waldron, (2020). Globally, soybeans are the principal oilseeds produced followed by rapeseed, and particularly in Europe, Sunflower (Chen, Huang, Liu, Lai and Wang, 2019). Worldwide oilseed production in 2019/2020 by type (in million metric tons) is shown in Figure 1 whereas the consumption from 2013/2014 to 2019/2020 by type (in million metric tons) is shown in Figure 2.

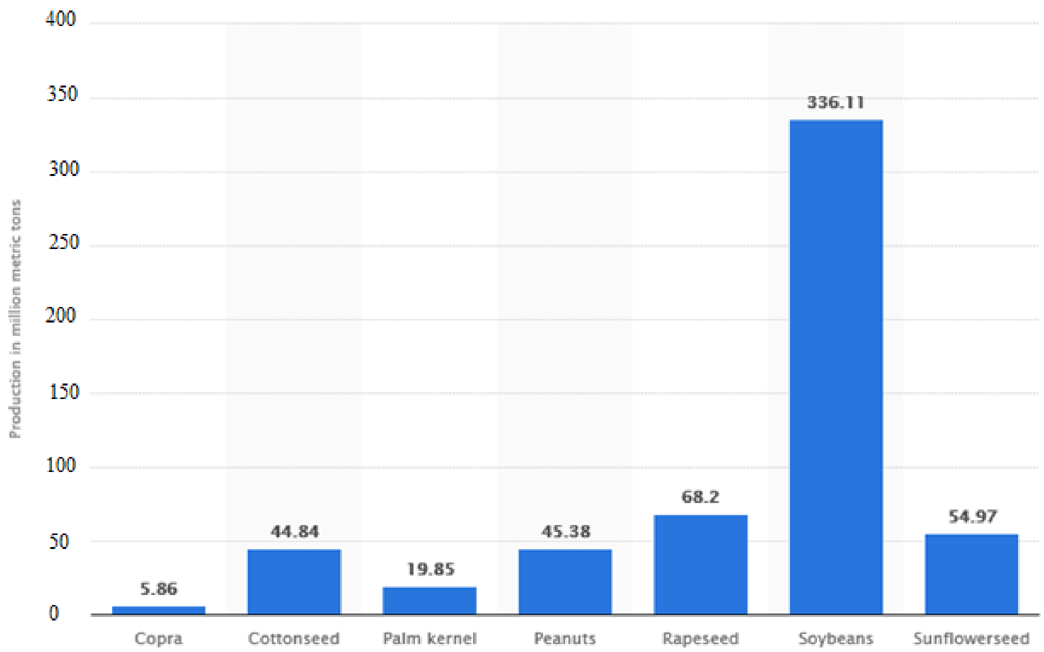

Figure 1. Worldwide oilseed production in 2019/2020 by type (in million metric tons). Source: https://www.statista.com/statistics/267271/worldwide-oilseed-production-since-2008/

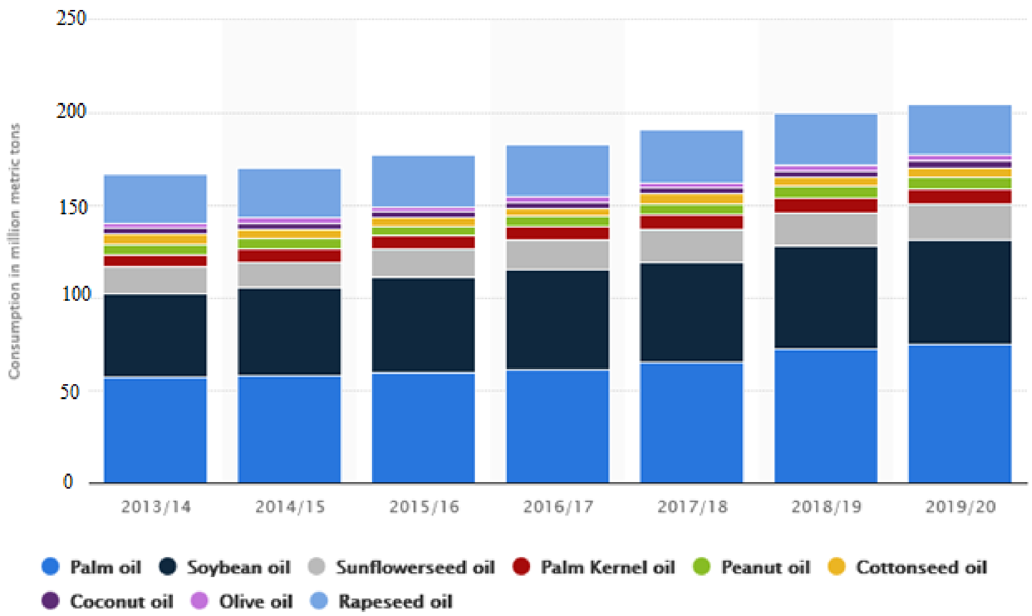

Figure 2. Consumption of vegetable oils worldwide from 2013/2014 to 2019/2020 by type (in million metric tons). Source: https://www.statista.com/statistics/263937/vegetable-oils-global-consumption/

2.2 Physical properties of oilseeds

The physical properties of oilseeds namely moisture content, unit mass, bulk/solid density, volume, porosity, surface area, arithmetic mean diameter, geometric mean diameter, sphericity, aspect ratio, coefficient of friction, and static/dynamic angle of repose have been considerably studied in the literature. Some of these studies include (Aviara, Onuh and Ehiabhi, 2010) on mucuna nuts; (Karaj and Muller 2010) on *Jatropha curcas* L. seeds and kernels; (Izli, Unal and Sincik, 2009) on rapeseed; (Sirisomboon and Kitchaiya 2009) on *Jatropha curcas* L. kernels after heat treatment; (Pradhan, Naik, Bhatnagar and Vijay, 2009) on tree-borne oilseed (Jatropha, Karanja and Simarouba); (Garnayak, Pradhan, Naik and Bhatnagar, 2008) on jatropha seed; (Ixtaina, Nolasco and Tomas, 2008) on chia seeds; (Kibar and Ozturk 2008) on soybean; (Coskuner and Karababa, 2007) on coriander seeds; (Mieszkalski, 1997) on the role of physical properties of seeds; (Sirisomboon, Kitchaiya, Pholpho, Mahuttanyavanitch, 2007) on *Jatropha curcas* L. fruits, nuts and kernels; (Tunde-Akintunde and Akintunde, 2004) on sesame seed and (Kachru, Gupta and Alam, 1994) on physicochemical constituents and engineering properties. In the aforementioned studies, the authors explained that the moisture content is important for the development of the drying process, adjustment, performance efficiency and energy consumption; gravimetric properties for the design of equipment related to aeration, drying, storage and transport; bulk density determines the capacity of storage and transport systems while true density is useful for separation equipment; porosity of the mass of seeds determines the resistance to airflow during aeration and drying. Frictional properties such as the angle of repose and the coefficient of friction are important for conveying systems, design of grain bins and other storage systems whose operation is influenced by the compressibility and flow behaviour of materials.

2.3 Mechanical properties and force-deformation curves of oilseeds

The mechanical properties and force-deformation characteristics of oilseeds have been studied by several authors including Kabutey et al., (2013) on jatropha seeds; Herak, Gurdil, Sedlacek, Dajbych and Simanjuntak (2010) on jatropha seeds; Gupta and Das, (2000) on sunflower seed and kernel and Lysiak, (2007) on a pea. The mechanical properties include rupture force, energy for rupture, deformation at rupture point, deformation ratio at rupture point, Young's modulus, toughness and hardness. According to Karaj and Muller (2010) and Sirisomboon, Kitchaiya, Pholpho and Mahuttanyavanitch (2007), the rupture force indicates the minimum force required for dehulling the fruit/shelling the nut and to extract the oil from the seed/kernel. The deformation at rupture point is the deformation at loading direction which can be used for the determination of the gap size between the surfaces to compress the fruit/nut for dehulling/shelling. Deformation ratio at rupture point is the axial strain at rupture point of the sample which is the ratio of deformation at rupture point to the dimension of the sample. Elastic/Young's modulus is the ratio of stress to strain and is often used by engineers as an index of product firmness. Toughness is the ratio of rupture energy to the volume of sample whereas hardness is the ratio of rupture force to the deformation at rupture point. Toughness and hardness are important attributes of agricultural materials for quality assessment. The force-deformation characteristics beyond the elastic limit can be used to simulate the occurrence of destruction in agricultural materials. Divisova et al., (2014) reported the study on deformation curve characteristics of rapeseeds and sunflower seeds. The authors indicated that the force-deformation curves of rapeseeds and sunflower seeds showed both smooth and wave-effect/serration effect patterns. The smooth curve pattern on the force deformation curve allows maximum oil output compared to the serration effect where minimum oil is obtained with the corresponding ejection of the seedcake through the holes of the pressing vessel. The energy required for causing rupture (failure) is characterised by the area under the force-deformation curve (Chakespari, Rajabipour and Mobli, 2010; Karaj and Muller, 2010; Zareiforoush, Komarizadeh and Alizadeh 2010). Besides, some authors including Lazouk et al., (2015); Izli, Unal and Sincik, (2009); Sharma, Sogi and Saxena, (2009); Gupta and Das (2000) and Bilanski (1996) have also studied the mechanical properties changes due to moisture content on soybean, sunflower and rapeseed. These studies reported a decrease of the force and rupture energy with the increase in moisture content required to initiate rupture of the seed coat, seed hull/kernel and energy absorbed.

2.4 Linear pressing (uniaxial compression) of oilseeds

According to Munson-Mcgee (2014), uniaxial pressure and screw expression are commonly used methods to apply mechanical pressure to express the liquid from the solid phase. The uniaxial process loads the material to be compressed into a pressing chamber (a known vessel diameter with a plunger) that contains holes at the bottom to allow oil leakage whiles the solid part is retained using a piston which is usually placed under the universal testing machine where the required force and speed are preset before the compression process.. The studies of Divisova et al., (2014); Herak, Gurdil, Sedlacek, Dajbych and Simanjuntak (2010) and Kabutey et al., (2013) used this method.

2.5 Non-linear pressing (screw expression) of oilseeds

In the screw expression process, the material is feed into the screw press through the hopper and the pressure is applied as the material is conveyed along the screw while the root of the screw increases in diameter (Munson-Mcgee, 2014). Screw presses are used at the industrial scale for continuous pressing of oilseeds. A screw press consists of a horizontal or vertical screw fitting closely inside a perforated cage where the oil is extracted (Bogaert, Mathieu, Mhemdi and Vorobiev, 2018). In Figures 3 and 4 are shown the mechanical press and components.

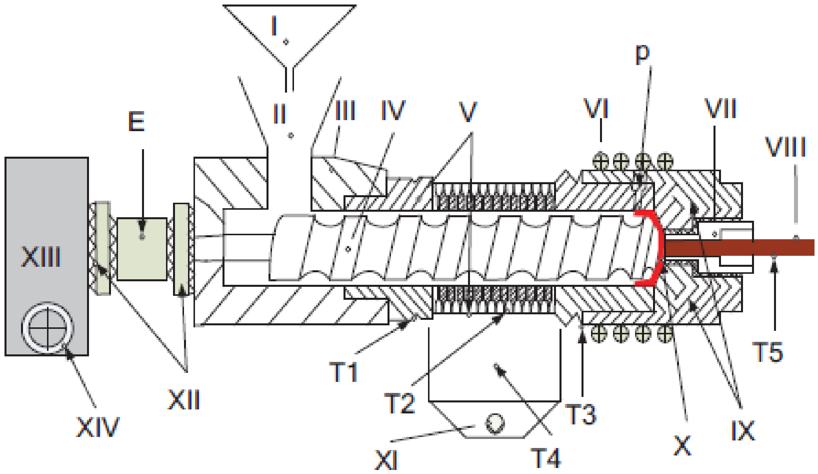

Figure 3. Mechanical screw press Komet D85-1G for oil extraction and installed sensors, (I) feeding container, (II) feeding hopper, (III) housing, (IV) screw, (V) press cylinder with oil outlet holes, (VI) heating, (VII) nozzle, (VIII) press cake, (IX) press head, (X) compression zone, (XI) oil collector, (XII) coupling, (XIII) motor, (XIV) speed alternator, (T1-T5) temperature sensors, (p) pressure sensor, (E) torque sensor. Source: Karaj and Muller, 2011.

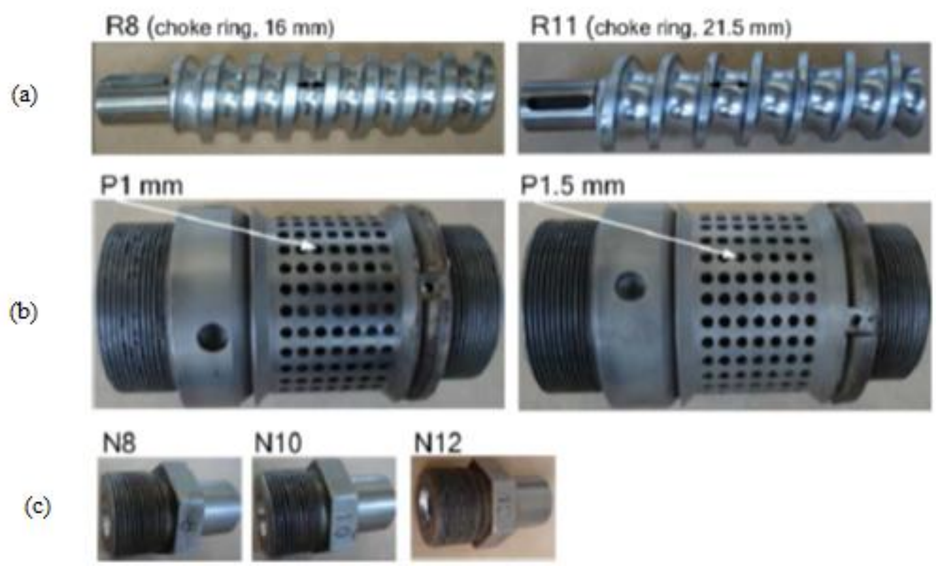

Figure 4. Independent variables of mechanical screw press Komet D85-1G. (a) Two different screws with choke worm shaft ring size 16 and 21.5 mm; (b) two different press cylinders with mesh size 1 and 1.5 mm and (c) three different nozzles with restriction size 8, 10 and 12 mm. Source: Karaj and Muller, 2011.

2.6 Response surface methodology

Response surface methodology (RSM) is an important tool used for developing models, statistically designing experiments and to evaluate the effects of different factors for searching for optimum conditions. The application of this technique is used in many fields such as environmental engineering, food technology and biotechnology among others (Dilipkumar, Rajamohan and Rajasimman, 2010; Rajasimman and Karthic, 2010; Rajeshkannan, Rajamohan and Rajasimman, 2010; Manivannan and Rajasimman, 2011; Rajeshkannan, Rajamohan and Rajasimman, 2011; Khatoon and Rai, 2020). RSM has several advantages among which is that it saves energy, time and resources by reducing the number of experimental runs required to evaluate multiple parameters with less difficulty (Zhong and Wang, 2010; Khatoon and Rai, 2020). As cited in Khatoon and Rai (2020), the design known as Box-Behnken design (BBD) is a type of response surface methodology that is rotatable and requires 3 levels of each factor. This design is more efficient, widely used in many studies and easier to systematize experiment. The polynomial model in BBD is used to fit the actual responses with a variety of optimal responses and determines the relationship among variables and responses (Abdollahi et al., 2012; Khatoon and Rai, 2020).

3 MATERIALS AND METHODS

3.1 Experimental location

The experiment was carried out at the laboratory of the Mechanical Department of Faculty of Engineering, Czech University of Life Sciences Prague.

3.2 Sample

Sample of bulk rapeseeds (Figure 5) purchased from Ceska Skalice, Czech Republic was used for the experiment.

3.3 Determination of moisture content

The moisture content of rapeseeds sample was determined to be 5.07 ± 0.20 (% w.b.) using Eq. (1) given by Blahovec (2008) and also mentioned in Chui (2020).

$$MC = \left[\left(\frac{m_b - m_a}{m_b}\right) \cdot 100\right] \tag{1}$$

where MC is the percentage of moisture content of the sample (% w.b.), m_a and m_b are the masses of the sample before and after oven drying (g).

3.4 Determination of oil content in rapeseeds sample

The percentage oil content contained in rapeseeds sample was determined to be 31.87 ± 2.40 % using the Soxhlet extraction procedure described by Niu et al., (2014), Danlami et al., (2015) and Gurkan et al., (2020) and also mentioned in Chui (2020).

3.5 Conditioning of initial moisture content of rapeseeds sample

The initial sample of moisture content of 5.07 ± 0.20 (5) % w.b. was conditioned at 70% and 80% relative humidity using the moisture conditioning equipment (MEMMERT GmbH + Co. KG, Germany) (Figure 6) for 24 h. Afterwards, the sample was put in the MEMMERT heating oven for another 24 h whereby the moisture contents of 8.42 ± 0.07 (8) % w.b. and 10.84 ± 0.51 (11) % w.b. (Figure 7) were respectively determined using Eq. (1) indicated above. The experiment was repeated twice and the results averaged.

Figure 5. Rapeseeds sample prepared for moisture conditioning

Figure 6. Moisture conditioning of rapeseeds sample at 80 % relative humidity.

Figure 7. Rapeseeds sample sealed in plastic bags after moisture content determination

3.6 Compression test of rapeseeds sample

The sample pressing height was measured at 60 mm using the vessel diameter of 60 mm (Figure 8). The compression tests were done using the universal compression testing machine (Tempos, ZDM 50, Czech Republic) where the forces and speeds were set. In total 17 experiments were conducted.

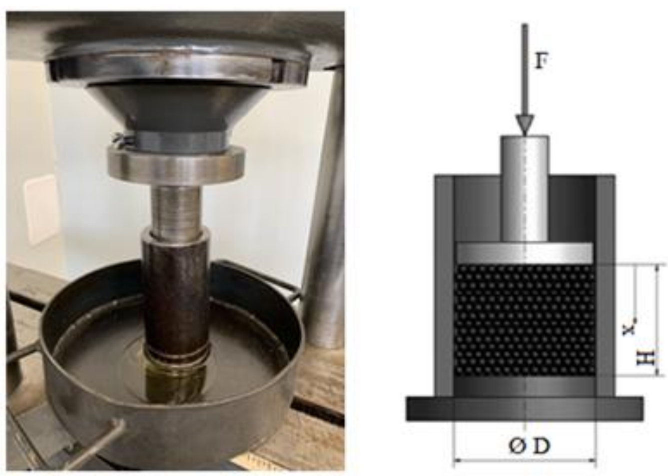

Figure 8. Schematic of pressing vessel diameter, D (mm) with a plunger; F: force (kN); H: initial pressing height of sample (mm) and x: sample deformation (mm) (Kabutey et al., 2015; Chui 2020).

3.6.1 Oil yield (%)

The oil yield was calculated based on the equation given by Deli et al., (2011)and Chanioti and Tzia, 2017 as given in Eq. (2).

$$O_{YD} = \left[\left(\frac{m_o}{m_s}\right) \cdot 100\right] \qquad (2)$$

where $O_{YD}$is percentage oil yield (%), m_o is the mass of oil obtained as the difference of mass of seedcake and initial mass of the sample m_s (g).

3.6.2 Oil expression efficiency (%)

The oil expression efficiency was calculated according to the equation given by Hernandez-Santos et al., (2016) as given in Eq. (3).

$$O_{EE} = \left[\left(\frac{OY}{O_s}\right) \cdot 100\right] \qquad (3)$$

where O_{EE} is the oil expression efficiency (%) and O_s is the percentage of oil content (%) in rapeseeds sample determined by soxhlet extraction.

3.6.3 Deformation energy (J)

The deformation energy (oil expression energy or energy) is characterized by the area under the force-deformation curve (Figure 9) (Gupta and Das 2000) which was calculated according to the relation given by Demirel et al., (2017), Divišová et al., (2014) as given in Eq. (4).

$$E_{NJ} = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2}\right) \cdot (x_{n+1} - x_n)\right] \qquad (4)$$

where $E_{NJ}$is the deformation energy (J), $F_{n+1} + F_n$ and $x_{n+1} - x_n$are the compressive force (kN) and deformation (mm), *n* is the number of data points and *i* is the number of sections in which the axis deformation was divided.

3.7 Box-Behnken Design (BBD)

3.7.1 Processing (Independent) factors

Three processing factors namely force, speed and moisture content were evaluated. Each factor was set at three levels: force (60, 80 and 100 kN); speed (5, 10 and 15 mm min^{-1}) and moisture content (5, 8 and 11% w.b.). The design of the experiment of the processing factors was done using the STATISTICA 13 software.

3.7.2 Coded processing factors

The processing factors were coded as (-1, 0 and +1) according to Ocholi et al., (2018) and Witek-Krowiak et al., (2014) and also mentioned in Chui (2020) as given in Eq. (5).

$$x_i = \frac{X_i - X_0}{\Delta X} \tag{5}$$

where x_i is the coded value of the i^{th} variable, X_i is the uncoded value of the i^{th} test variable and $X_0$is the uncoded value of the ith test variable at the centre point.

3.7.3 Regression model

The regression model describing the Box-Behnken Design (BBD) according to Huang et al., (2019) and also mentioned in Chui (2020) is given in Eq. (6).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i_{1<j}}^{k} \sum_{j}^{k} \beta_{ij} X_i X_j \tag{6}$$

where Y is the response variable; i and j are linear and quadratic coefficients; β_0, β_i, β_{ii} and β_{ij} are the regression coefficients in the intercept, linear, quadratic and interaction terms respectively; X_i and X_j are the independent variables and k is the number of factors.

3.8 Statistical analysis

The data were statistically analyzed using STATISTICA 13 software (Statsoft 2010) by applying the response surface regression technique.

4 RESULTS AND DISCUSSION

4.1 Mass of oil output and deformation of rapeseeds

The mass of oil and deformation of rapeseeds at different force, speed and moisture content combinations are given in Table 1. The maximum oil output of 9.56 g was obtained at the force of 80 kN, speed of 5 mm min^{-1} and moisture content of 5% (w.b.). At force 60 kN, speed of 10 mm min^{-1} and moisture content of 11% (w.b.) there was no oil leakage. This could be due to the lower force and higher speed, which did not allow more time for the release of the oil. Therefore, the minimum amount of oil recorded was at force of 80 kN, speed of 15 mm min^{-1} and moisture content of 11% (w.b.). The deformation values did not linearly correlate with the amount of oil leakage or mass of oil. For instance, the mass of oil of 7.34 g at deformation value of 27.47 mm for the processing factors combination (force of 100 kN, speed of 10 mm min^{-1} and moisture content of 5% (w.b.)) was lower than the deformation value of 26.95 mm which recorded the mass oil of 7.585 g for the combination of the variables (force of 100 kN, speed of 5 mm min^{-1} and moisture content of 8% (w.b.)).

Table 1. Determination of mass of rapeseed oil and deformation at different forces, speeds and moisture contents.

Run	Force F_x (kN)	Speed S_x (mm min^{-1})	Moisture content M_x (% w.b.)	M_{BP} (g)	M_{AP} (g)	M_{OT} (g)	D_{FX} (mm)
1	60	5	8	119.295	117.96	1.335	25.84
*2	100	5	8	119.295	111.71	7.585	26.95
3	60	15	8	119.295	118.28	1.015	24.70
*4	100	15	8	119.295	111.25	8.045	24.81
5	60	10	5	115	109.83	5.17	27.39
6	100	10	5	115	107.66	7.34	27.47
7	60	10	11	122.365	122.365	0	25.13
*8	100	10	11	122.365	121.76	0.605	25.91
9	80	5	5	115	105.44	9.56	29.71
10	80	15	5	115	110.52	4.48	26.41
*11	80	5	11	122.365	120.07	2.295	26.32
*12	80	15	11	122.365	122.2	0.165	25.48
*13	80	10	8	119.295	114.17	5.125	23.50
14	80	10	8	119.295	114.31	4.985	24.84
15	80	10	8	119.295	114.92	4.375	24.50
16	80	10	8	119.295	112.37	6.925	25.58
17	80	10	8	119.295	113.5	5.795	23.92

* Serration effect on the force deformation curve; M_{BP}: Mass of bulk seeds before pressing (g); M_{AP}: Mass of bulk seeds after pressing (g);M_{OT}: Mass of oil output (g) and D_{FX}: Deformation of bulk seeds (mm)

4.2 Relationship between force and deformation curves

The force and deformation curves of rapeseeds at the processing conditions showed both smooth curve and serration effect characteristics. The serration-effect behaviour was shown at the processing conditions of (force of 100 kN, speed of 5 mm min^{-1} and moisture content of 8% (w.b.)), force of 100 kN, speed of 15 mm min^{-1} and moisture content of 8% (w.b.)), force of 100 kN, speed of 10 mm min^{-1} and moisture content of 11% (w.b.)), force of 80 kN, speed of 5 mm min^{-1} and moisture content of 11% (w.b.)), force of 80 kN, speed of 15 mm min^{-1} and moisture content of 11% (w.b.)) and force of 80 kN, speed of 10 mm min^{-1} and moisture content of 8% (w.b.)) respectively. The rest of the combination of the variables showed smooth curves

(Table 1). The smooth curve pattern on the force-deformation curve explains the maximum leakage of the oil whereas the serration effect is related to the minimum oil output as a result of the ejection of the seedcake through the holes of the pressing vessel. In Figure 9 is shown the force-deformation curve characteristics of rapeseed sample. In Appendixes is also presented the other force-deformation curve behaviours where the maximum force limits were determined.

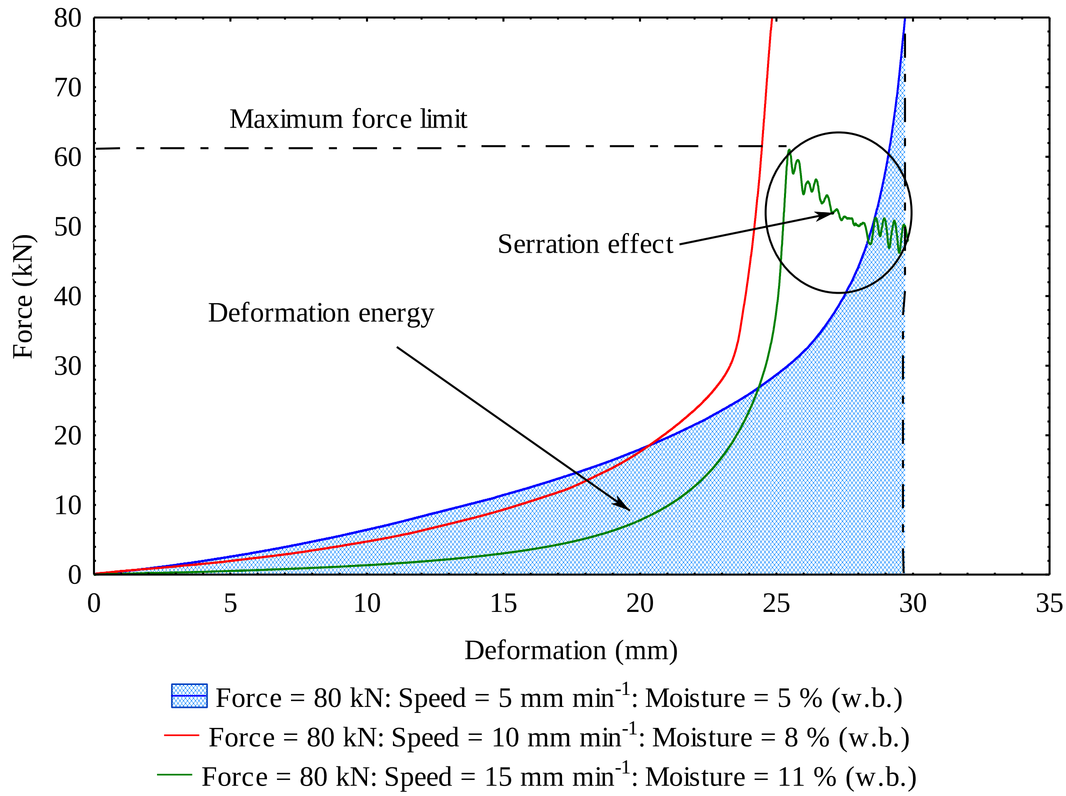

Figure 9. Force-deformation curve characteristics for different speeds and moisture contents

4.3 Oil yield, oil expression efficiency and energy of rapeseeds

The oil yield (%), oil expression efficiency (%) and energy of rapeseeds at the processing factors combination are given in Table 2. The amounts of oil yield and oil expression efficiency are related to the mass of oil as described earlier. At the force of 80 kN, speed of 5 mm min^{-1} and moisture content of 5% (w.b.) with the maximum mass of oil, oil yield and oil expression efficiency; the energy value was 462.31 J. This energy was obtained at the smooth curve behaviour on the force-deformation curve indicating the efficient energy for obtaining the maximum oil. It is worth mentioning that although some serration effect behaviours were observed on the force-deformation curve, their energies were calculated from the area under the force-deformation curve without the serration effect to be similar to the energies from the area under the force-deformation curve with smooth curve behaviour as far as energy efficiency in relation to oil output is concerned. Based on the results higher energy did not relate to higher oil recovery efficiency.

Table 2. Amounts of oil yield, oil expression efficiency and energy of bulk rapeseeds at different forces, speeds and moisture contents.

Runs	Force F_x (kN)	Speed S_x (mm min^{-1})	Moisture content M_x (% w.b.)	O_{YD} (%)	O_{EE} (%)	E_{NJ} (J)
1	60	5	8	1.12	3.51	179.11
*2	100	5	8	6.36	19.95	282.03
3	60	15	8	0.85	2.67	181.76
*4	100	15	8	6.74	21.16	224.11
5	60	10	5	4.50	14.11	386.66
6	100	10	5	6.38	20.03	447.04
7	60	10	11	0.00	0.00	129.23
*8	100	10	11	0.49	1.55	144.03
9	80	5	5	8.31	26.08	462.31
10	80	15	5	3.90	12.22	398.21
*11	80	5	11	1.88	5.88	153.65
*12	80	15	11	0.13	0.42	148.90
*13	80	10	8	4.30	13.48	243.66
14	80	10	8	4.18	13.11	271.23
15	80	10	8	3.67	11.51	277.21
16	80	10	8	5.80	18.21	296.44
17	80	10	8	4.86	15.24	291.25

* Serration effect on the force deformation curve; O_{YD}: Oil yield (%); O_{EE}: Oil expression efficiency (%); E_{NJ}: Energy (J).

4.4 Determined regression models of oil yield, oil expression efficiency and energy

For the response surface regression analysis, the coded input factors and their responses are given in Table 3. The statistical results of oil yield (%) and oil expression efficiency are given in Tables 4 and 5 respectively. The linear terms of force and moisture content were significant (P < 0.05) whereas the rest of the terms (linear, quadratic and interactions) were not significant

(P > 0.05). The model F-value of 4.06 and probability value (P < 0.05) confirm that the model is significant. The models representing oil yield and oil expression efficiency are described in Eqs. 7 and 8 respectively. The statistical result of energy is presented in Table 6. The linear and quadratic terms of force and moisture content were significant (P < 0.05) whereas the other terms and the interactions were not significant (P > 0.05). The model F-value of 59.30 and probability value (P < 0.05) confirms that the model is significant. The model representing energy is described in Eq. 9. The work of Chanioti and Tzia (2017) used a similar approach to evaluate the data on oil from olive pomace using response surface methodology.

Table 3. Coded input factors based on the Box Behnken Design for the response surface regression analysis.

Runs	Force F_x (kN)	Speed S_x (mm min^{-1})	Moisture content M_x (% w.b.)	O_{YD} (%)	O_{EE} (%)	E_{NJ} (J)
1	-1	-1	0	1.12	3.51	179.11
*2	1	-1	0	6.36	19.95	282.03
3	-1	1	0	0.85	2.67	181.76
*4	1	1	0	6.74	21.16	224.11
5	-1	0	-1	4.50	14.11	386.66
6	1	0	-1	6.38	20.03	447.04
7	-1	0	1	0.00	0.00	129.23
*8	1	0	1	0.49	1.55	144.03
9	0	-1	-1	8.31	26.08	462.31
10	0	1	-1	3.90	12.22	398.21
*11	0	-1	1	1.88	5.88	153.65
*12	0	1	1	0.13	0.42	148.90
*13	0	0	0	4.30	13.48	243.66
14	0	0	0	4.18	13.11	271.23
15	0	0	0	3.67	11.51	277.21
16	0	0	0	5.80	18.21	296.44
17	0	0	0	4.86	15.24	291.25

* Serration effect on the force deformation curve; O_{YD}: Oil yield (%); O_{EE}: Oil expression efficiency (%); E_{NJ}: Energy (J)

Table 4. Response surface regression results of oil yield (%).

Source	Coefficients	Standard error	Sum of squares	DF	Mean square	F-value	P-value.
Model	4.56	0.70	89.4	9	9.94	4.06	0.04
F_X	1.69	0.55	22.78	1	22.78	34.63	0.00
F_X^2	-0.75	0.76	2.39	1	2.39	3.63	0.13
S_X	-0.76	0.55	4.58	1	4.58	6.95	0.06
S_X^2	-0.04	0.76	0.01	1	0.01	0.01	0.92
M_X	-2.57	0.55	52.99	1	52.99	80.55	0.00
M_X^2	-0.97	0.76	3.93	1	3.93	5.97	0.07
$F_X \cdot S_X$	0.16	0.78	0.11	1	0.11	0.16	0.71
$F_X \cdot M_X$	-0.35	0.78	0.48	1	0.48	0.73	0.44
$S_X \cdot M_X$	0.67	0.78	1.77	1	1.77	2.69	0.18
Residual			17.14	7	2.45		
Lack of Fit			14.51	3	4.84	7.35	0.04
Total			106.59	16			

F_X: Force (kN); S_X: Speed (mm min^{-1}); M_X: Moisture content (% w.b.); DF: Degree of freedom; Coefficient of determination (R^2): 0.84;F-value > P-value or P-value < 0.05 is significant; F-value < P-value or P-value > 0.05 is non-significant.

$$O_{YD} = 4.56 + 1.69 \cdot F_X - 2.57 \cdot M_X \quad (7)$$

Table 5. Response surface regression results of oil expression efficiency (%).

Source	Coefficients	Standard error	Sum of squares	DF	Mean square	F-value	P-value
Model	14.31	2.20	880.7	9	97.86	4.06	0.04
F_X	5.30	1.74	224.72	1	224.72	34.51	0.00
F_X^2	-2.36	2.39	23.40	1	23.40	3.59	0.13
S_X	-2.37	1.74	44.89	1	44.89	6.89	0.06
S_X^2	-0.13	2.39	0.07	1	0.07	0.01	0.92
M_X	-8.07	1.74	521.48	1	521.48	80.09	0.00
M_X^2	-3.03	2.39	38.66	1	38.66	5.94	0.07
$F_X \cdot S_X$	0.51	2.46	1.05	1	1.05	0.16	0.71
$F_X \cdot M_X$	-1.09	2.46	4.77	1	4.77	0.73	0.44
$S_X \cdot M_X$	2.10	2.46	17.64	1	17.64	2.71	0.18
Residual			168.81	7	24.12		
Lack of Fit			142.76	3	47.59	7.31	0.04
Total			1049.55	16			

F_X: Force (kN); S_X: Speed (mm min^{-1}); M_X: Moisture content (% w.b.); DF: Degree of freedom; Coefficient of determination (R^2): 0.84;F-value > P-value or P-value < 0.05 is significant; F-value < P-value or P-value > 0.05 is non-significant.

$$O_{EE} = 14.31 + 5.30 \cdot F_X - 8.07 \cdot M_X \quad (8)$$

Table 6. Response surface regression results of energy (J).

Source	Coefficients	Standard error	Sum of squares	DF	Mean square	F-value	P-value
Model	275.96	8.21	179783.4	9	19975.93	59.30	0.00
F_X	27.56	6.49	6074.8	1	6074.78	14.12	0.02
F_X^2	-36.62	8.95	5645.3	1	5645.34	13.13	0.02
S_X	-15.52	6.49	1925.7	1	1925.72	4.48	0.10
S_X^2	-22.59	8.95	2148.5	1	2148.48	5.00	0.09
M_X	-139.80	6.49	156355.1	1	156355.12	363.52	0.00
M_X^2	37.40	8.95	5889.0	1	5889.04	13.69	0.02
$F_X \cdot S_X$	-15.14	9.18	917.2	1	917.18	2.13	0.22
$F_X \cdot M_X$	-11.40	9.18	519.4	1	519.38	1.21	0.33
$S_X \cdot M_X$	14.84	9.18	880.6	1	880.61	2.05	0.23
Residual			2358.33	7	336.90		
Lack of Fit			637.9	3	212.6	0.49	0.71
Total			182141.7	16			

F_X: Force (kN); S_X: Speed (mm min^{-1}); M_X: Moisture content (% w.b.); DF: Degree of freedom; Coefficient of determination (R^2): 0.99; F-value > P-value or P-value < 0.05 is significant; F-value < P-value or P-value > 0.05 is non-significant.

$$E_{NJ} = 275.96 + 27.56 \cdot F_X - 36.62 \cdot F_X^2 - 139.80 \cdot M_X + 37.40 \cdot M_X^2 \qquad (9)$$

4.5 Optimum processing factors for maximum responses

The determined processing factors optimal for oil yield, oil expression efficiency and energy are given in Table 7. The profiles for predicted values, desirability values and regression models predicted values are also given in Table 8. Profiles for predicted values and desirability of oil yield (%), oil expression efficiency (%) and energy (J) in relation to the optimized force, speed and moisture content at 4 and 20 iteration steps are illustrated in Figures 10 to 15 respectively. For oil yield and oil expression efficiency, the desirability value of 0.97 from 1 was observed. For energy, the desirability values of 0.99 and 1 were found at 4 and 20 iteration steps respectively. Based on the optimized processing factors, the oil yield and oil expression efficiency were achieved at 8.82 % and 27.68 %. The energy values were 450.72 J and 451.57 J respectively. These optimized values need to be validated in the future study.

Table 7. Determined optimum processing factors (actual and coded values) for maximum responses of rapeseeds.

Responses	Force F_x (kN)	Speed S_x (mm min^{-1})	Moisture content M_x (% w.b.)
Oil yield (%)	100 (+1)	5 (-1)	5 (-1)
Oil expression efficiency (%)	100 (+1)	5 (-1)	5 (-1)
Energy (J)	90 (+0.5)	5 (-1)	5 (-1)
	96 (+0.8)	6.5 (-0.7)	5 (-1)

Table 8. Predicted responses based on the profiles and regression models.

Responses	Profiles predicted values	*Desirability values	**Regression models predicted values
Oil yield (%)	8.67	0.98	8.82
Oil expression efficiency (%)	27.22	0.98	27.68
Energy (J)	478.81	0.99	450.72
	479.54	1.00	451.57

*Significant coefficients of the independent factors (P-value < 0.05); **Higher desirability value between 0 and 1 denotes reliability of the profiles predicted value for the optimized processing factors.

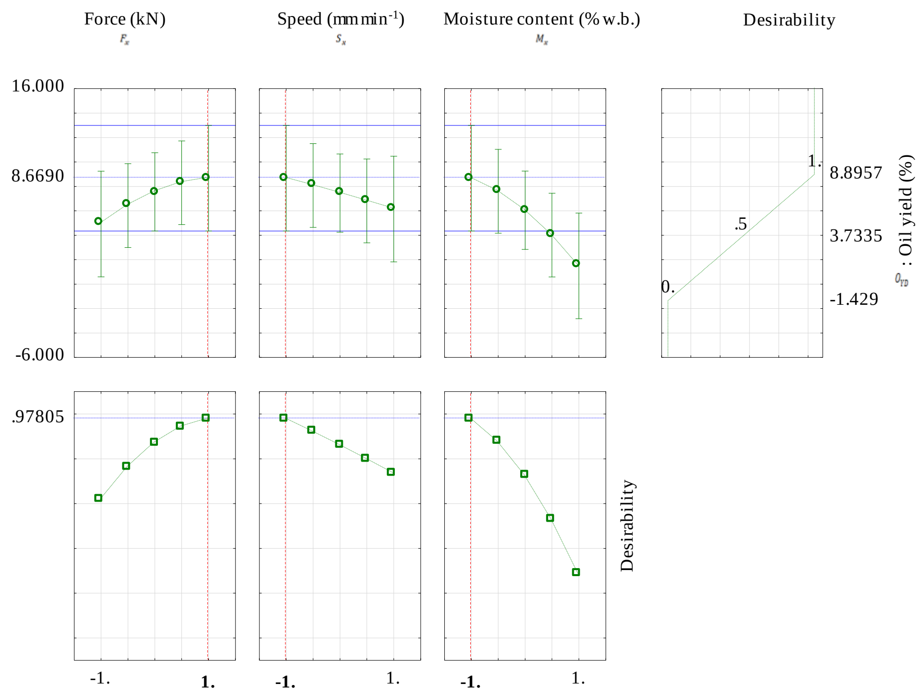

Figure 10. Profiles for predicted values and desirability of oil yield (%) in relation to force, speed and moisture content at 4 iteration steps.

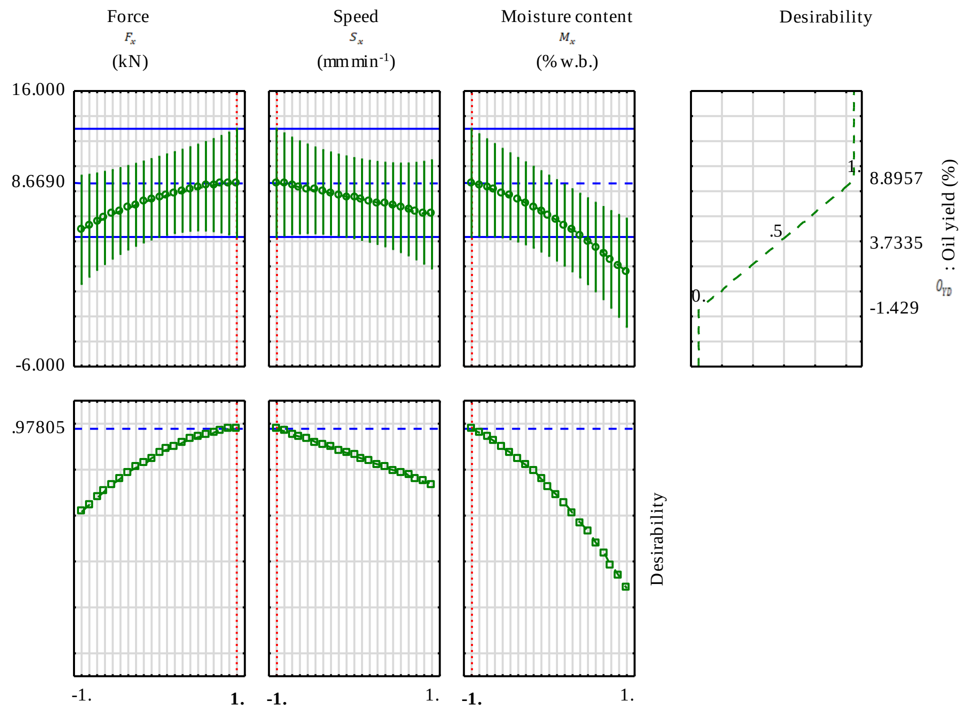

Figure 11. Profiles for predicted values and desirability of oil yield (%) in relation to force, speed and moisture content at 20 iteration steps.

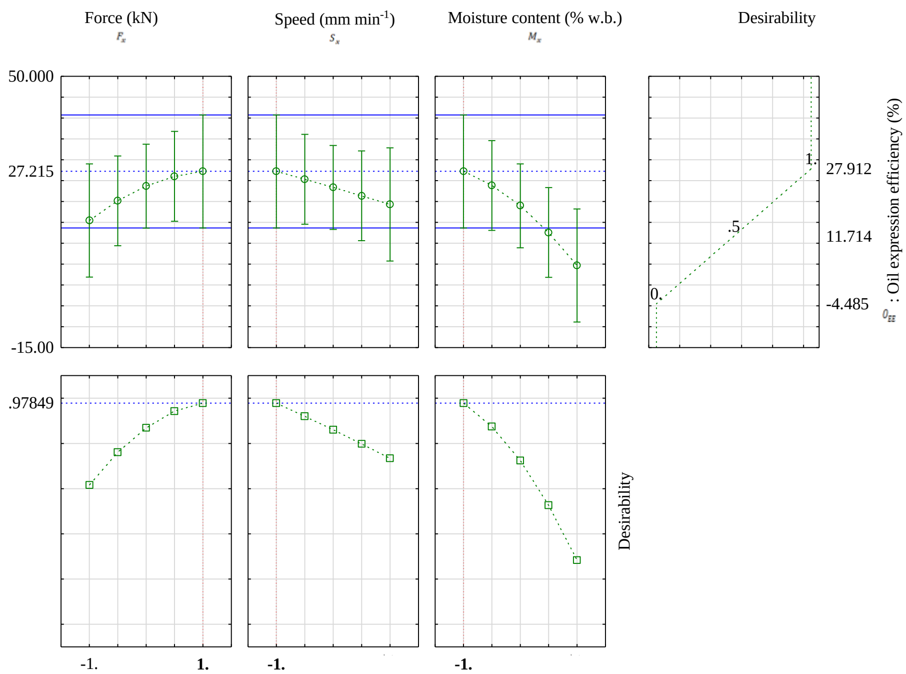

Figure 12. Profiles for predicted values and desirability of oil expression efficiency (%) in relation to force, speed and moisture content at 4 iteration steps.

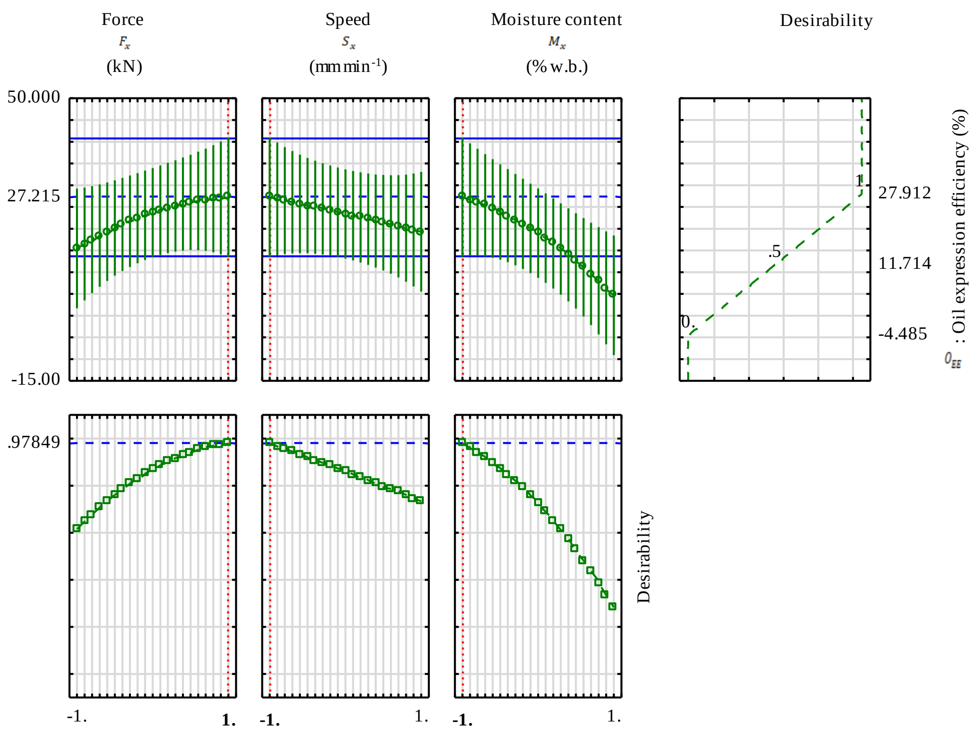

Figure 13. Profiles for predicted values and desirability of oil expression efficiency (%) in relation to force, speed and moisture content at 20 iteration steps.

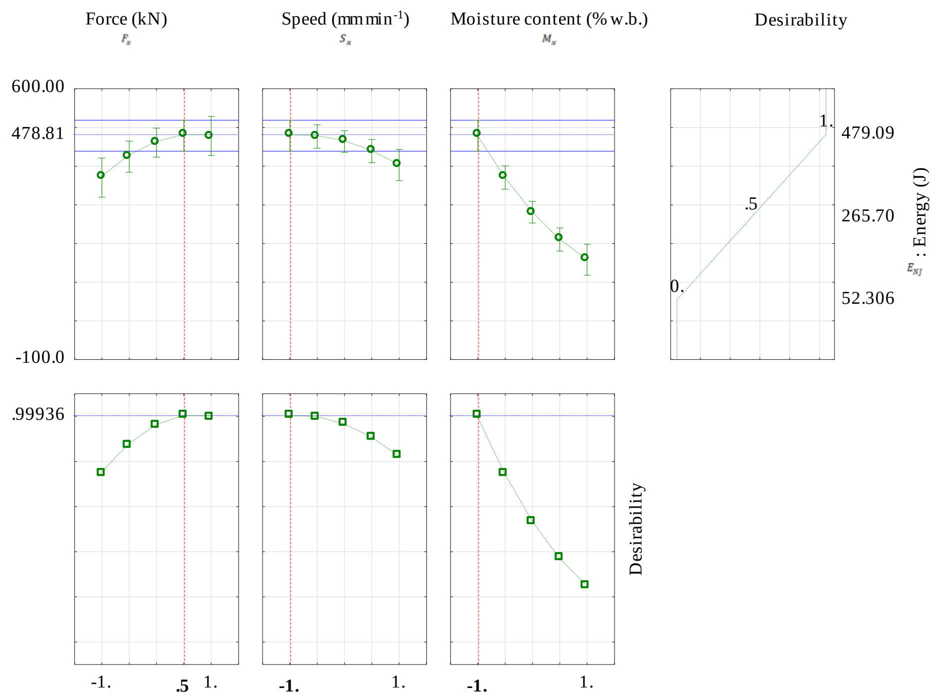

Figure 14. Profiles for predicted values and desirability of energy (J) in relation to force, speed and moisture content at 4 iteration steps.

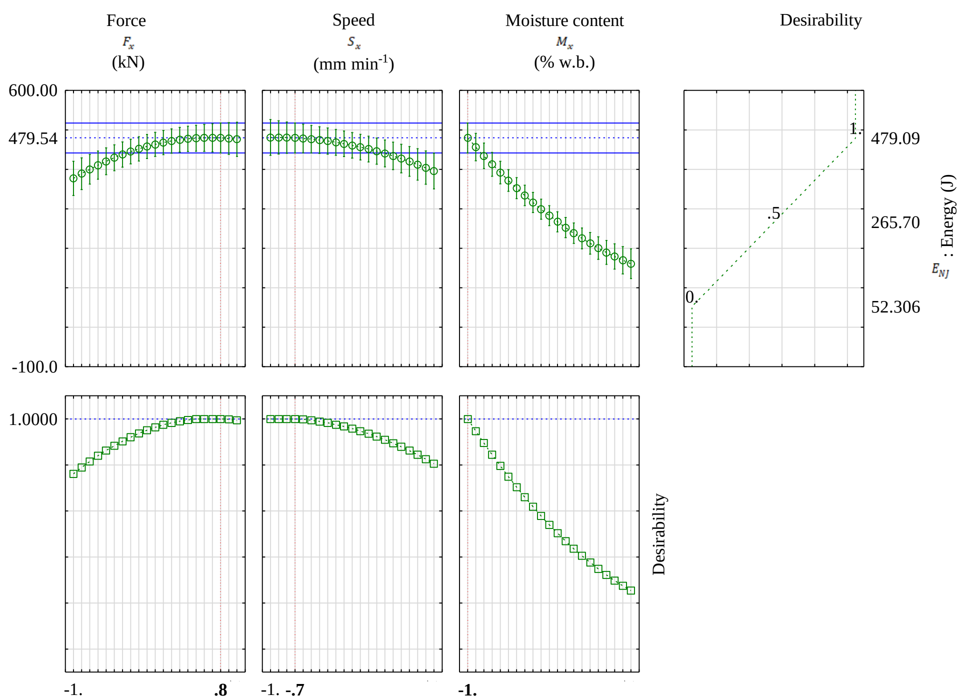

Figure 15. Profiles for predicted values and desirability of energy (J) in relation to force, speed and moisture content at 20 iteration steps.

4.6 Evaluation of regression models adequacy

The observed, predicted and residuals of oil yield, oil expression efficiency and energy as well as the plots of normality and predicted versus residuals are presented in Tables 9 to 11 and Figures 16 to 18 respectively. It can be seen that the data showed approximately normally distributed suggesting the reliability of the results. Equations (Eqs. 10 to 12) were used to determine the predicted values whereas the residuals were the difference between the observed and the predicted. The adequacy of the models was further evaluated based on the lack of Fit P-values (Tables 6 to 8) respectively for oil yield, oil expression efficiency and energy. The lack of Fit values of oil yield and oil expression efficiency was less than the probability value of 5% ($P < 0.05$). This indicates that the models for oil yield and oil expression efficiency were not adequate for prediction. In contrast to energy, the model was adequate for prediction since the lack of Fit P-value was greater than the probability value of 5% ($P > 0.05$).

Table 9. Observed, predicted and residuals of oil yield (%)

Runs	*Force F_x (kN)	*Speed S_x (mm min^{-1})	*Moisture content M_x (% w.b.)	Observed	Predicted	Residuals
1	-1	-1	0	1.12	3.00	-1.88
2	1	-1	0	6.36	6.05	0.31
3	-1	1	0	0.85	1.16	-0.31
4	1	1	0	6.74	4.86	1.88
5	-1	0	-1	4.50	3.38	1.12
6	1	0	-1	6.38	7.45	-1.07
7	-1	0	1	0.00	-1.07	1.07
8	1	0	1	0.49	1.61	-1.12
9	0	-1	-1	8.31	7.55	0.76
10	0	1	-1	3.90	4.71	-0.81
11	0	-1	1	1.88	1.07	0.81
12	0	1	1	0.13	0.89	-0.76
13	0	0	0	4.30	4.56	-0.26
14	0	0	0	4.18	4.56	-0.38
15	0	0	0	3.67	4.56	-0.89
16	0	0	0	5.80	4.56	1.24
17	0	0	0	4.86	4.56	0.30

*Coded values of the actual values

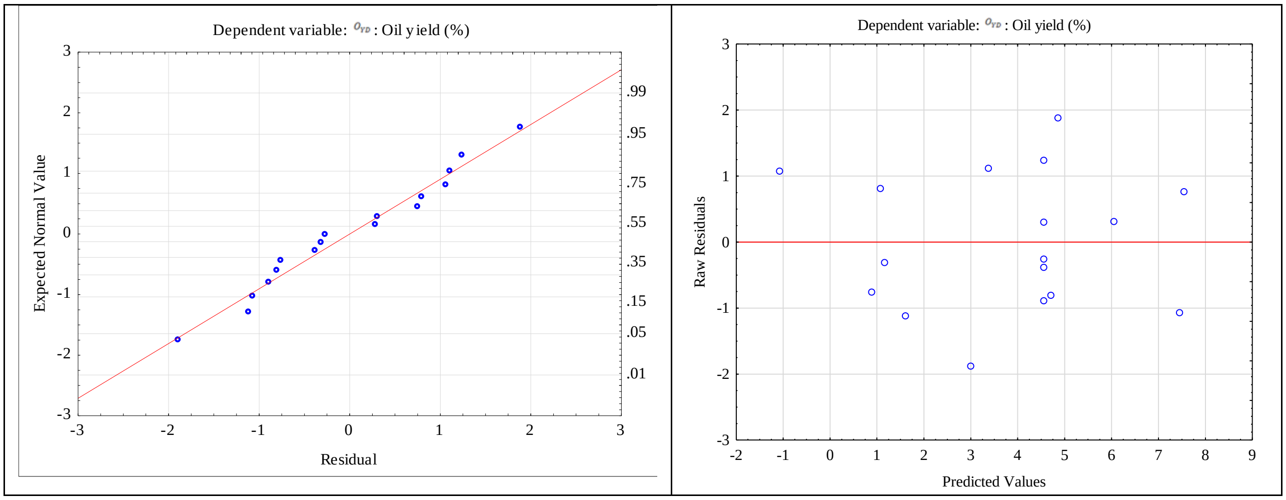

Figure 16. Plots of normality and predicted versus residuals of oil yield (%).

$$O_{YD} = 4.56 + 1.69 \cdot F_X - 0.75 \cdot F_X^2 - 0.76 \cdot S_X - 0.04 \cdot S_X^2 - 2.57 \cdot M_X - 0.97 \cdot M_X^2 + 0.16 \cdot F_X \cdot S_X - 0.35 \cdot F_X \cdot M_X + 0.67 \cdot S_X \cdot M_X \qquad (10)$$

Table 10. Observed, predicted and residuals of oil expression efficiency (%)

Runs	*Force F_x (kN)	*Speed S_x (mm min^{-1})	*Moisture content M_x (% w.b.)	Observed	Predicted	Residuals
1	-1	-1	0	3.51	9.40	-5.89
2	1	-1	0	19.95	18.98	0.97
3	-1	1	0	2.67	3.64	-0.97
4	1	1	0	21.16	15.27	5.89
5	-1	0	-1	14.11	10.60	3.51
6	1	0	-1	20.03	23.39	-3.36
7	-1	0	1	0.00	-3.36	3.36
8	1	0	1	1.55	5.06	-3.51
9	0	-1	-1	26.08	23.69	2.39
10	0	1	-1	12.22	14.76	-2.54
11	0	-1	1	5.88	3.35	2.54
12	0	1	1	0.42	2.81	-2.39
13	0	0	0	13.48	14.31	-0.83
14	0	0	0	13.11	14.31	-1.20
15	0	0	0	11.51	14.31	-2.80
16	0	0	0	18.21	14.31	3.90
17	0	0	0	15.24	14.31	0.93

*Coded values of the actual values of the processing factors

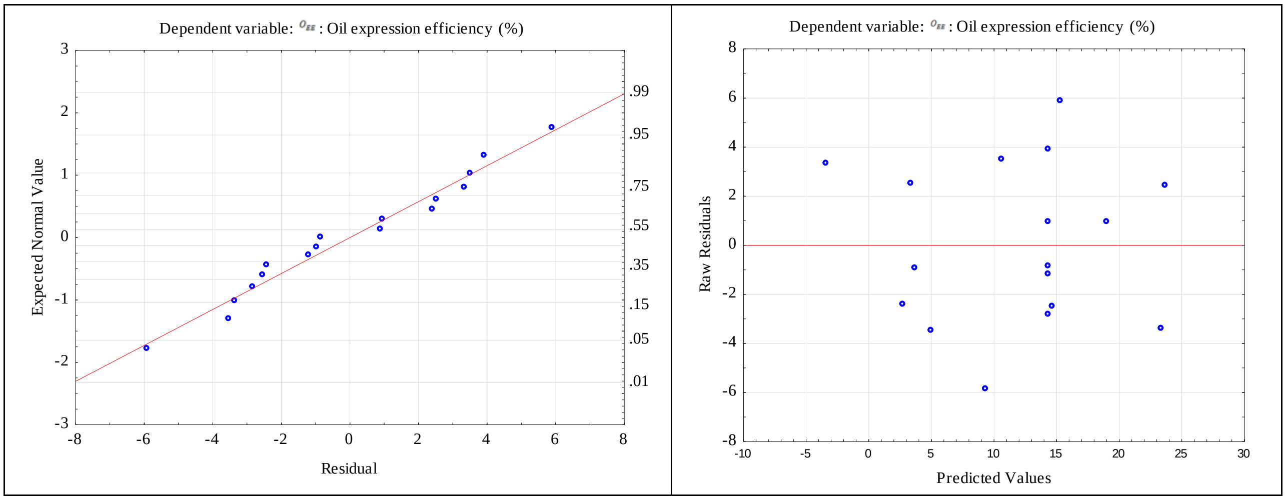

Figure 17. Plots of normality and predicted versus residuals of oil expression efficiency (%).

$$O_{EE} = 14.31 + 5.30 \cdot F_X - 2.36 \cdot F_X^2 - 2.37 \cdot S_X - 0.13 \cdot S_X^2 - 8.07 \cdot M_X - 3.03 \cdot M_X^2 + 0.51 \cdot F_X \cdot S_X - 1.09 \cdot F_X \cdot M_X + 2.10 \cdot S_X \cdot M_X \quad (11)$$

Table 11. Observed, predicted and residuals of energy (J)

Runs	*Force F_x (kN)	*Speed S_x (mm min^{-1})	*Moisture content M_x (% w.b.)	Observed	Predicted	Residuals
1	-1	-1	0	179.11	189.57	-10.46
2	1	-1	0	282.03	274.97	7.06
3	-1	1	0	181.76	188.82	-7.06
4	1	1	0	224.11	213.65	10.46
5	-1	0	-1	386.66	377.59	9.07
6	1	0	-1	447.04	455.49	-8.45
7	-1	0	1	129.23	120.78	8.45
8	1	0	1	144.03	153.10	-9.07
9	0	-1	-1	462.31	460.92	1.39
10	0	1	-1	398.21	400.22	-2.01
11	0	-1	1	153.65	151.64	2.01
12	0	1	1	148.90	150.29	-1.39
13	0	0	0	243.66	275.96	-32.30
14	0	0	0	271.23	275.96	-4.73
15	0	0	0	277.21	275.96	1.25
16	0	0	0	296.44	275.96	20.48
17	0	0	0	291.25	275.96	15.29

*Coded values of the actual values of the processing factors

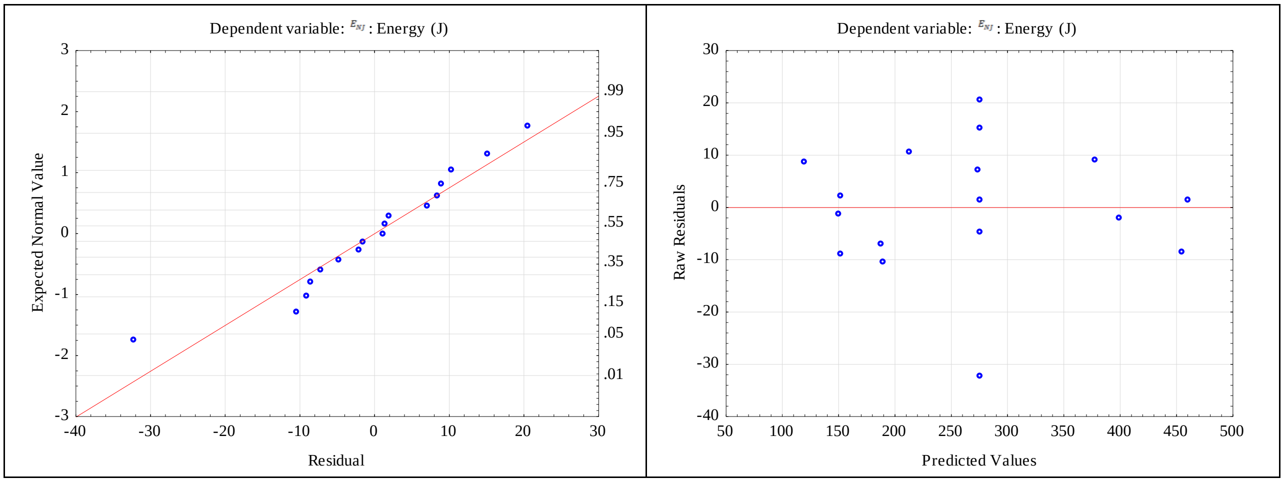

Figure 18. Plots of normality and predicted versus residuals of energy (J).

$$E_{NJ} = 275.96 + 27.56 \cdot F_X - 36.62 \cdot F_X^2 - 15.52 \cdot S_X - 22.59 \cdot S_X^2 - 139.80 \cdot M_X + 37.40 \cdot M_X^2 - 15.14 \cdot F_X \cdot S_X - 11.40 \cdot F_X \cdot M_X + 14.84 \cdot S_X \cdot M_X \quad (12)$$

4.7 Effects of compression factors on oil yield and energy in non-linear pressing involving mechanical screw press

According to Mrema and McNulty (1985), as cited in Bargale (2000), the mechanical pressing of oilseeds is the most common method of edible oil extraction. The main reason for its use is that it provides a non-contaminated and protein-rich low-fat deoiled cake at relatively low-cost. However, extraction efficiency is usually between 50 and 80% compared to solvent extraction method which is capable of recovering 98% (Bargale, 1997). Modifications in press design, press components and optimization of process variables through experimentation have been the efforts considered to improve the performance of mechanical pressing of oilseeds (Bargale, 2000; Karaj and Muller, 2011; Evon, Kartika, Cerny and Rigal, 2013; Uitterhaegen and Evon, 2017). The literature indicates that pressure, heating temperature, pressing time, particle size, speed and moisture content are the factors which affect oil yield during expression processing of oilseeds (Mrema and McNulty, 1985; Ajibola, Adetunji and Owolarafe, 2000; Baryeh, 2001; Olayanju, Akinoso and Oresanya, 2006; Mwithiga and Moriasi, 2007; Deli, Farah, Tajul and Wan, 2011).

Karaj and Muller, 2011 indicated that lower energy input means lower oil recovery efficiency, higher oil residue in press cake and higher speed material throughput. The authors further mentioned that theoretically, higher screw speed means more speed material throughput and higher oil content residual in press cake since less time is available for the oil to drain from solids (Beerens, 2007; Willems, Kuipers and de Haan, 2008, 2009).

Theoretically, oil yield would increase with the increase of heating temperature and pressure (Deli, Farah, Tajul and Wan, 2011; Karaj and Muller, 2011; Willems, Kuipers and de Haan, 2009, 2008). But under a certain level, the increase of heating temperature will probably decrease the amount of oil yield due to the change of moisture content and structure of the seeds during the heating process (Adeeko and Ajibola, 1990; Hamzat and Clarke, 1993; Baryeh, 2001).

Singh, Wiesenborn, Tostenson and Kangas (2002) stated that the screw pressing of uncooked crambe seed showed that the residual oil content decreased as seed moisture content decreased. The authors observed that lower moisture content of 5.9% was important compared to 4.1% which was not beneficial due to the occurrence of more sediment in the oil. Furthermore, the authors stated that the oil recovery of soaked and sun-dried flaxseed increased from 78% to 88% as moisture content increased from 5% to 7%. But at 9% moisture content, the oil recovery decreased to 76%. The authors explained that higher moisture content increased plasticity and thereby reduced the level of compression, which contributed to poor oil recovery. Another explanation given was that moisture acted as a lubricant in the barrel therefore higher moisture content resulted in insufficient friction during pressing (Hoffmann, 1989; Singh and Bargale, 1990; Reuber, 1992).

5 CONCLUSIONS

i. The maximum oil output of 9.56 g was obtained at a force of 80 kN, speed of 5 mm min^{-1} and moisture content of 5 % (w.b.).

ii. The deformation values did not linearly correlate with the amount of oil leakage. The force and deformation curves of rapeseeds at the processing conditions showed both smooth curve and serration effect characteristics.

iii. At the force of 80 kN, speed of 5 mm min^{-1} and moisture content of 5 % (w.b.) with the maximum mass of oil, oil yield and oil expression efficiency; the energy value was 462.31 J. Higher energy did not relate to higher oil recovery efficiency.

iv. For oil yield and oil expression efficiency regression models, the linear terms of force and moisture content were significant ($P < 0.05$) whereas the other terms and their interactions were not significant ($P > 0.05$). For energy, the linear and quadratic terms of force and moisture content were significant ($P < 0.05$) whereas the linear and quadratic terms of speed and the interaction terms of the factors were not significant ($P > 0.05$).

v. The optimal processing factors for oil yield and oil expression efficiency were found at force of 100 kN, speed of 5 mm min^{-1} and moisture content of 5 % (w.b.) whereas that of energy were forces of 90 and 96 kN, speed of 5 and 6.5 mm min-1 and moisture content of 5 % (w.b.).

vi. Based on the optimized processing factors, the oil yield and oil expression efficiency were predicted as 8.82 % and 27.68 %. The energy values were 450.72 J and 451.57 J respectively.

vii. The effects of the processing factors on oil yield and energy requirement of rapeseeds in non-linear pressing involving mechanical screw presses were discussed based on the literature.

6 RECOMMENDATIONS

(i) Validation of the predicted responses for the optimized processing factors should be considered in the future study.

(ii) Different varieties of rapeseeds should be considered in the future study to compare with the oil expression efficiency and energy demand in relation to the optimized processing factors.

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8 INTERNET SOURCES

https://www.statista.com/statistics/267271/worldwide-oilseed-production-since-2008/

https://www.statista.com/statistics/263937/vegetable-oils-global-consumption/

9 APPENDIXES

Figure 19.The student loading rapeseeds samples into the moisture conditioning equipment.

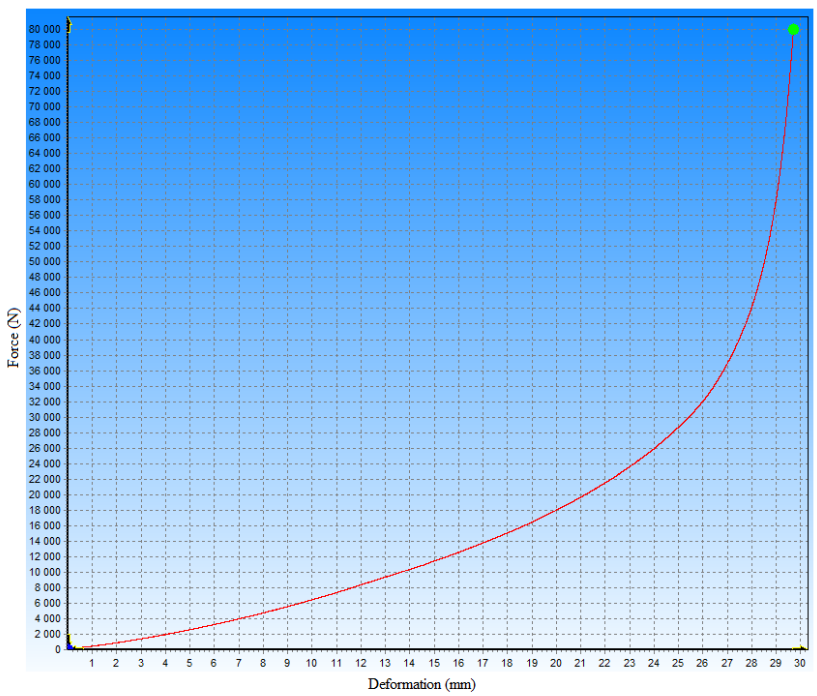

Figure 20. Force-deformation curve for force 80 kN.speed 5 mm min^{-1} and moisture 5 % (w.b.) showing smooth curve behaviour (without serration effect)

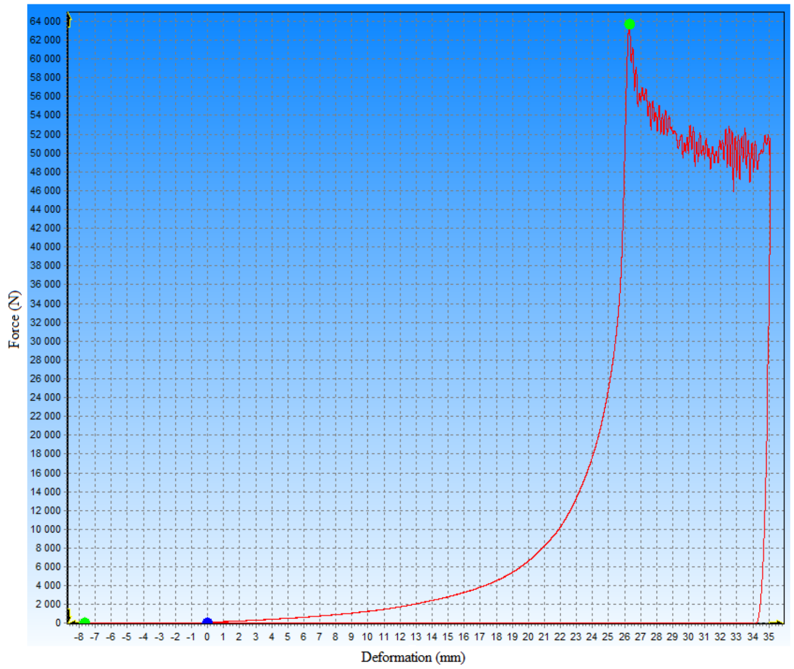

Figure 21. Force-deformation curve for force 80 kN.speed 5 mm min^{-1} and moisture 11 % (w.b.) showing the serration effect at maximum force 64 kN.

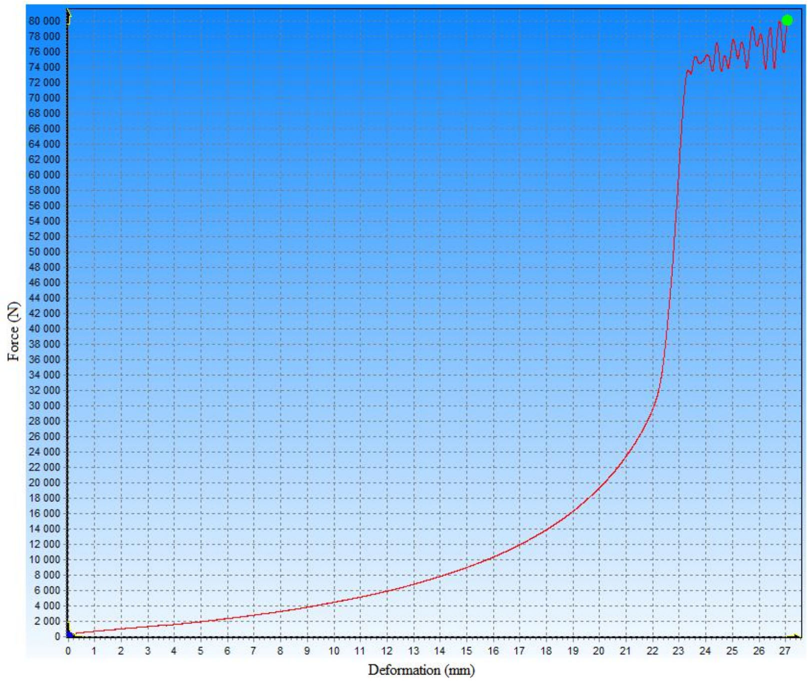

Figure 22. Force-deformation curve for force 80 kN.speed 10 mm min^{-1} and moisture 8 % (w.b.) showing the serration effect at maximum force 74 kN.

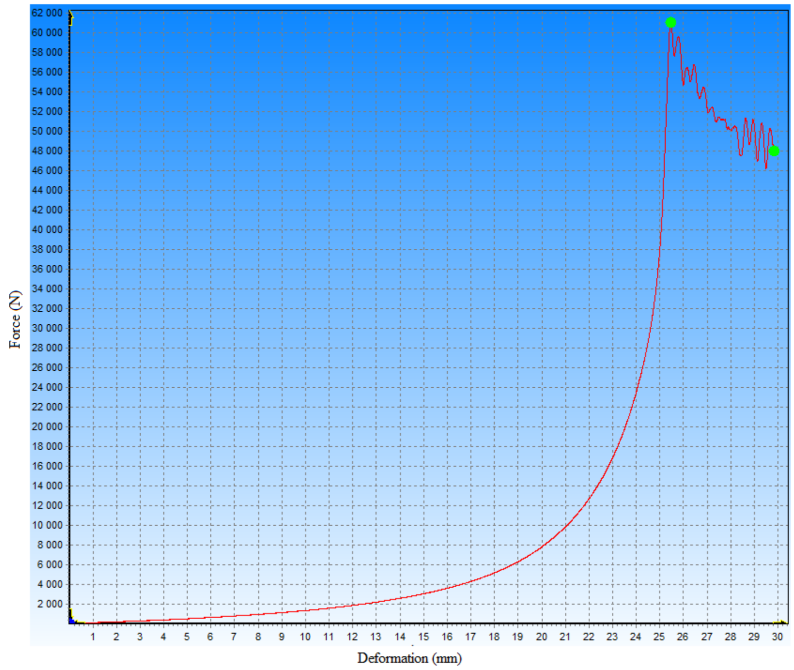

Figure 23.Force-deformation curve for force 80 kN.speed 15 mm min^{-1} and moisture 11 % (w.b.) showing the serration effect at maximum force 61 kN.

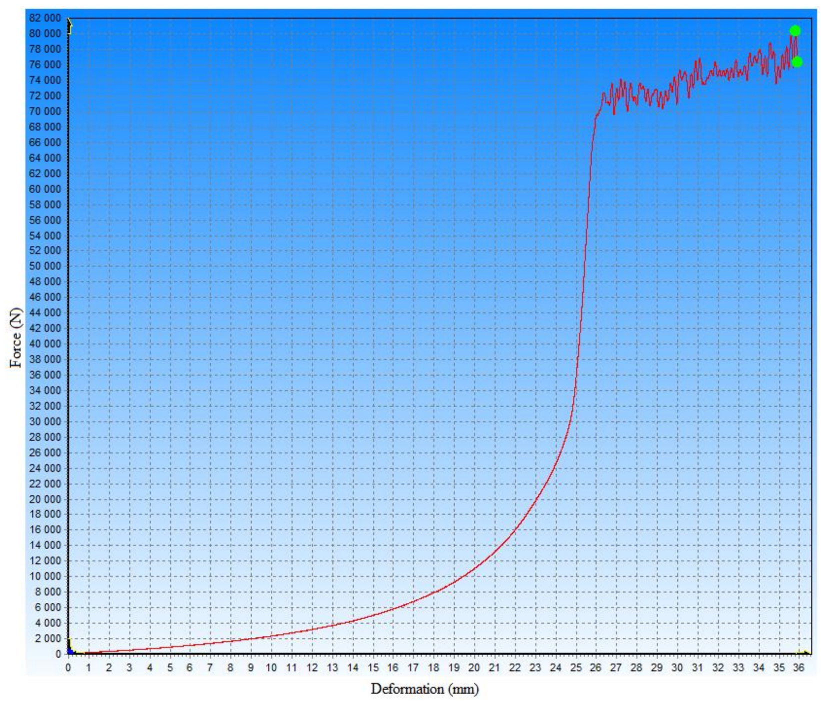

Figure 24. Force-deformation curve for force 100 kN.speed 5 mm min^{-1} and moisture 8 % (w.b.) showing the serration effect at maximum force 72 kN.

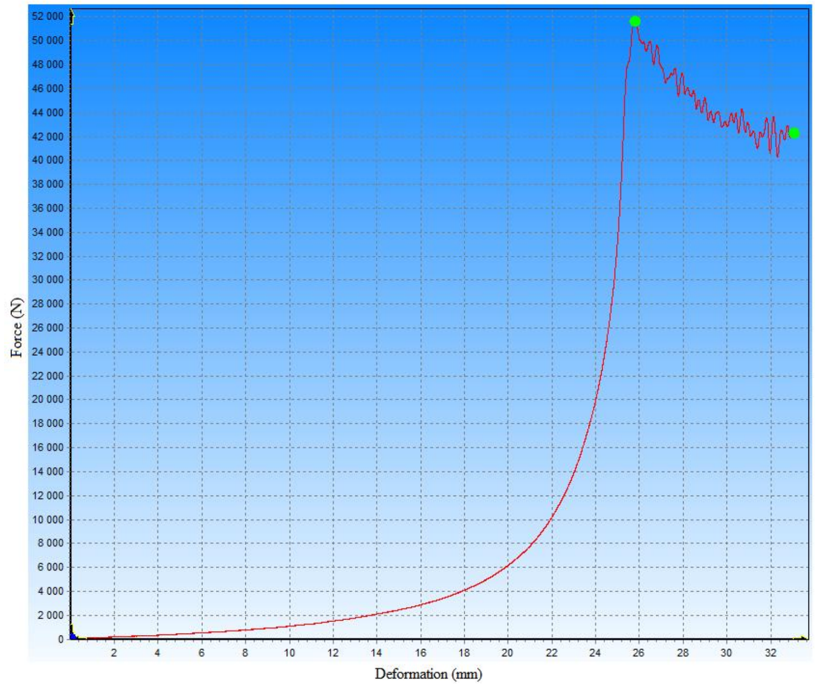

Figure 25. Force-deformation curve for force 100 kN.speed 10 mm min^{-1} and moisture 11 % (w.b.) showing the serration effect at maximum force 51 kN.

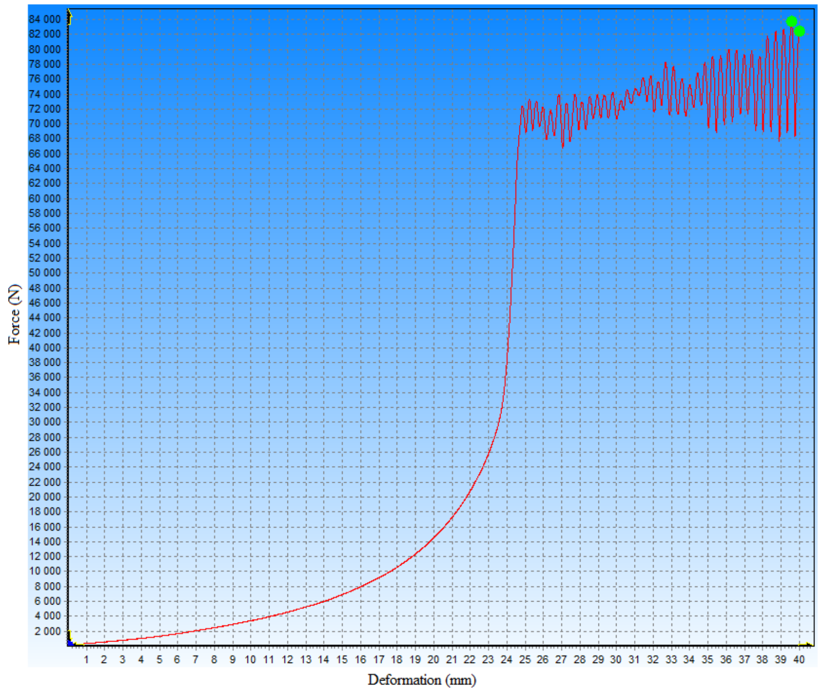

Figure 26. Force-deformation curve for force 100 kN. speed 15 mm min^{-1} and moisture 8 % (w.b.) showing the serration effect at maximum force 72 kN