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Application of a tangent curve mathematical model for analysis of the mechanical behaviour of sunflower bulk seeds

Riswanti Sigalingging[1,2]*, *David Herák*[2], *Abraham Kabutey*[2], *Oldřich Dajbych*[2], *Petr Hrabě*[3], *and Čestmír Mizera*[2]

[1] Department of Agricultural Engineering, University of Sumatera Utara,
Prof. A. Sofyan No. 3 Kampus USU, Medan, Indonesia Republic
[2]Department of Mechanical Engineering, [3]Department of Material Science and Manufacturing Technology,
Czech University of Life Sciences Prague, Kamycka 129, Praha 6, Czech Republic

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A b s t r a c t. This paper evaluate the use of a tangent curve mathematical model for representation of the mechanical behaviour of sunflower bulk seeds. Compression machine (Tempos Model 50, Czech Republic) and pressing vessel diameter 60 mm were used for the loading experiment. Varying forces between 50 and 130 kN and speeds ranging from 10, 50, and 100 mm min^{-1} were applied respectively on the bulk seeds with moisture content 12.37±0.38% w.b. The relationship between force and deformation curves of bulk seeds of pressing height 80 mm was described. The oil point strain was also determined from the different deformation values namely 30, 35, 40, and 45 mm at speed 10 mm min^{-1}. Based on the results obtained, model coefficients were determined for fitting the experimental load and deformation curves. The validity of these coefficients were dependent on the bulk seeds of pressing height, vessel diameter, maximum force 110 kN, and speed 10 mm min^{-1}, where optimal oil yield was observed. The oil point was detected at 45 mm deformation giving the strain value of 0.56 with the corresponding force 16.65±3.51 kN and energy 1.06±0.18 MJ m^{-3}. At the force of 130 kN, a serration effect on the curves was indicated; hence, the compression process was ceased.

K e y w o r d s: oil bearing crop, linear compression, energy requirement, oil point, Mathcad 14 software

INTRODUCTION

Sunflower (*Helianthus annuus* L.) is an annual plant belonging to the family (*Asteraceae*) growing up to a height of 4.6 m. The plant has large, rough, and hairy leaves and flower heads grow between 20 and 30 cm in diameter. The seeds, which are oval in shape, contain very nutritious oil composition including vitamins (B-1, B-5, B-6), tannins, inulin, levulin, magnesium, selenium, phosphorus, tryptophan, copper, magnesium, folate, fiber, iron, zinc, amino acids, and Omega-3 fatty acid (Arsah and Amjad, 2012; Madhavi *et al.,* 2010). Sunflower oil is also suitable for non-food purposes such as biodiesel or vegetable-oil based fuel for many vehicles (Pereyra-Irujo *et al.,* 2009).

For medicinal use, sunflower seeds possess antioxidant, anti-inflammatory, diuretic, and expectorant properties. These include the reduction of asthma symptoms, osteoarthritis, and rheumatoid arthritis as well as bronchial, pulmonary, and laryngeal problems. They can also be applied as an addition to therapy of colon cancer, high blood pressure, and migraine headaches. As a result of its magnesium content, the seeds can be used against heart attacks and strokes. Sunflower leaves can also be used as an infusion to treat high fevers, lung problems, and diarrhea, and the roots against snake and spider bites (Arsah and Amjad, 2012; Madhavi *et al.,* 2010).

For extraction of oil from bulk seeds, mechanical pressing has been the most common technique especially in the rural areas of developing countries. Other methods such as solvent, enzyme assisted, and supercritical fluid extractions have been feasible for oil extraction from sunflower seeds and other oilseeds. The combination of mechanical pressing and solvent extraction processes gives better

*Corresponding author e-mail: riswanti@usu.ac.id

results than either method applied individually. In spite of all these available methods, factors such as pressure, temperature, pressing time, and moisture content greatly affect oil yield during extraction processes of oilseeds (Evon *et al.,* 2014; Khan and Hanna 1983; Willems *et al.,* 2008). To improve the oil extraction and energy utilization efficiency using mechanical methods such as screw presses or expellers, modification in press design and optimization of process parameters have been considered (Toscano and Pedretti, 2007). Mathematical models based on Darcy law and simulation programmes including a linear programme for optimization and a discrete element method (Mrema and McNulty, 1985; Owolarafe *et al.,* 2008; Raji and Favier 2004) have also been employed in modelling and optimization of oil recovery efficiency. These processes revealed that pressure is the most vital variable for consideration, since higher pressure increases oil percentage although it could generate higher temperature, which subsequently affects the quality of the oil either for food or biofuel production (Omobuwajo *et al.,* 1998; Venter *et al.,* 2007; Willems *et al.,* 2008).

In monitoring and setting the required pressure for pressing the oil from oilseeds, it is necessary to understand the mechanical behaviour of bulk oilseeds and their mathematical description under compression loading (Gupta and Das, 1997). In the literature, such studies have been described in detail on jatropha bulk oilseeds compared to other oilseed crops such as rape, soybean, safflower, sunflower *etc*., where most studies have been focused on moisture-dependent physical and engineering properties (Bhise *et al.,* 2013; de Figueiredo *et al.,* 2011; Mirzabe *et al.,* 2012; Moya *et al.,* 2013; Tarighi *et al.,* 2011). In compression loading, the bulk oilseed is measured into a pressing vessel or chamber with holes beneath, which allows leakage of the oil while the solid part or the seed cake remains in the pressing vessel. The oil yield in this case is usually determined as the ratio of the mass of oil (the difference between initial mass of bulk seeds and mass of press cake) to that of the initial mass of bulk seeds. For example, the oil yield of jatropha bulk seeds has been found to range between 0.88±0.05 and 27.45±0.13 g, depending on the bulk seeds moisture content, pressing height, vessel diameter, amount of force, and speed (Kabutey *et al.,* 2015).

Based on the compression test, a mathematical model applying the tangent curve function has been developed for describing the mechanical behaviour and the deformation characteristic curve of different bulk oilseeds. The tangent curve function (Herák *et al.,* 2011) is described as follows:

$$F(x) = A\left[\tan(B\,x)\right]^{n},$$

where: A is the force coefficient of the mechanical behaviour (N), B is the deformation coefficient of the mechanical behaviour (mm^{-1}), and n is the exponent of the fitted curve function. The Mathcad 14 software with the Levenberg-Marquardt algorithm for data fitting optimal for tangent curve approximation provides a very simple mathematical algorithm for the tangent curve mathematical model development. The application of the software does not require advanced computer memory for data processing unlike simulation programmes such as the finite element method (Petrů *et al.,* 2012). From the point of experimental and mathematical knowledge, the development of the tangent curve mathematical model takes into account the compression loading boundary conditions. These boundary conditions are as follows: when the force is increasing to infinity, the deformation reaches the maximum limit, zero compressive force means zero deformation, and the integral of the tangent curve function is the energy.

Identification of the oil point of bulk oilseeds is also relevant to the dynamics of the mechanical behaviour, which is influenced by such factors as porosity, contact pressure, gradients of pressure, and compressibility (Faborode and Favier, 1996; Herák *et al.,* 2013; Omobuwajo *et al.,* 1998; Rusinek *et al.,* 2012). In-depth information of oil point detection of sunflower bulk seeds in compression loading is required to develop suitable mathematical models for the description of the compression process by maximizing oil yield efficiency with minimum energy utilization.

The aim of the study was to describe the load-deformation characteristics of sunflower bulk seeds based on the tangent curve mathematical model. Parameters such as deformation, energy, oil yield, oil point strain, oil point force, and oil point energy were evaluated.

MATERIALS AND METHODS

Sunflower bulk seeds purchased from Ceska Skalice, Czech Republic, were subjected to a mechanical compression test using a compression machine (Tempos Model 50, Czech Republic). A pressing vessel diameter 60 mm with a plunger was used. Various compressive forces from 50, 70, 90, 110, and 130 kN and speed 10, 50, and 100 mm min^{-1} were applied on the bulk seeds of pressing height 80 mm.

The initial moisture content of the bulk seeds was determined using the standard hot air oven method with a temperature setting of 105°C and a drying time of 17 h (ISI, 1966). The electronic balance (Kern 440–35, Kern & Sohn GmbH, Balingen, Germany) with an accuracy of 0.001g was used for weighing the samples before and after oven drying. The mean moisture content of sunflower bulk seeds 12.37±0.38% w.b. was calculated using the equation given by (Blahovec, 2008). The data obtained was a repetition of three experiments which was analyzed by ANOVA using STATISTICA software (Statsoft, 2010) and Mathcad software 14 (MathCAD 14, PTC Software, Needham MA, USA), (Pritchard, 1988), which uses the Levenberg-Marquardt algorithm for data fitting (Marquardt, 1963).

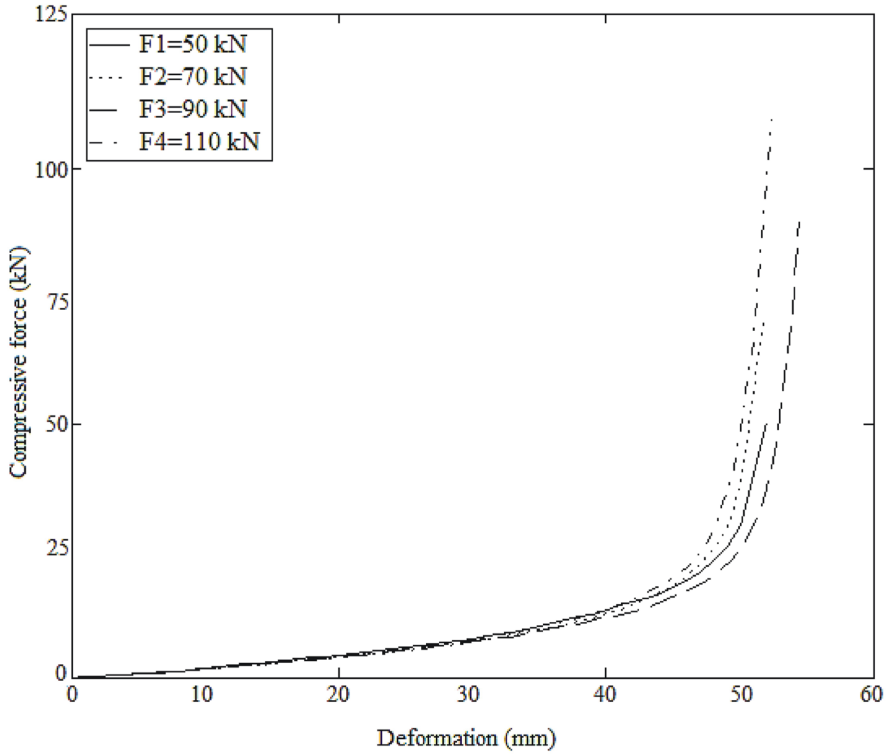

Fig. 1. Compressive force and deformation characteristic curves of sunflower bulk seeds at speed 10 mm min^{-1}.

The Mathcad algorithm makes use of function derivations to search coefficients for fitting the experimental data. The oil yield was determined using the equation reported by Kabutey *et al.* (2015).

The deformation energy which represents the area under the force-deformation curve was calculated applying the equation given by (Sigalingging *et al.,* 2014). The oil point or the first leakage of the oil was visually observed from the positions of the 0.2 mm holes of the vessel diameter for each deformation value of 30, 35, 40, and 45 mm applied on the bulk sunflower seeds (Herák *et al.,* 2013).

RESULTS AND DISCUSSION

The dependence between the force and deformation curves of sunflower bulk seeds in relation to the varying forces at a constant speed 10 mm min^{-1} is illustrated in (Fig. 1). Similar results were observed at constant speeds 50 and 100 mm min^{-1}. Higher force of 130 kN demonstrated a serration effect on the deformation curves. This behaviour contributed to ejection of crushed sunflower seeds through the positions of the 0.2 mm holes beneath the pressing vessel. As a result, the compression test was set at maximum force of 110 kN. The serration effect has been also reported among the bulk seeds of jatropha, rape, and sunflower at constant force of 100 kN and speed 60 mm min^{-1} (Divišová *et al.,* 2014). The experimental relationship between the force and deformation characteristic curve of sunflower bulk seeds was theoretically fitted by the tangent curve model (Sigalingging *et al.,* 2014). Figure 2 shows the experimental data fitted by the tangent curve model at speed 10 mm min^{-1} and maximum force 110 kN, for which the highest oil yield of the sunflower bulk seeds was obtained. Statistical analysis of the tangent model coefficients determined for fitting the experimental data are presented in Table 1. The results were statistically significant based on the evaluation that the critical values (F_{crit}) were higher than the value of F-tests (F_{ratio}) as well as p-values being greater than the significant value of 0.05. The coefficients of determination (R^2) values of the determined model coefficients also explain the suitability of the tangent curve mathematical model for representation of deformation curve characteristics of sunflower bulk seeds under compression loading. The validity of these coefficients is limited from zero deformation to maximum deformation of the bulk seeds. It also depends on the bulk seeds pressing height, vessel diameter, maximum force and speed.

Tables 2 and 3 present the experimental and statistical results of the measured parameters of sunflower bulk seeds. For deformation, the different forces at constant speeds 10 and 50 mm min^{-1} were not statistically significant ($p>0.05$) compared to speed 100 mm min^{-1}, which was significant ($p<0.05$).

On the other hand, oil yield and energy were statistically significant ($p<0.05$). Obviously, higher speed reduces the residence time of the oil to discharge from the bulk oilseeds (Kabutey *et al.,* 2015).

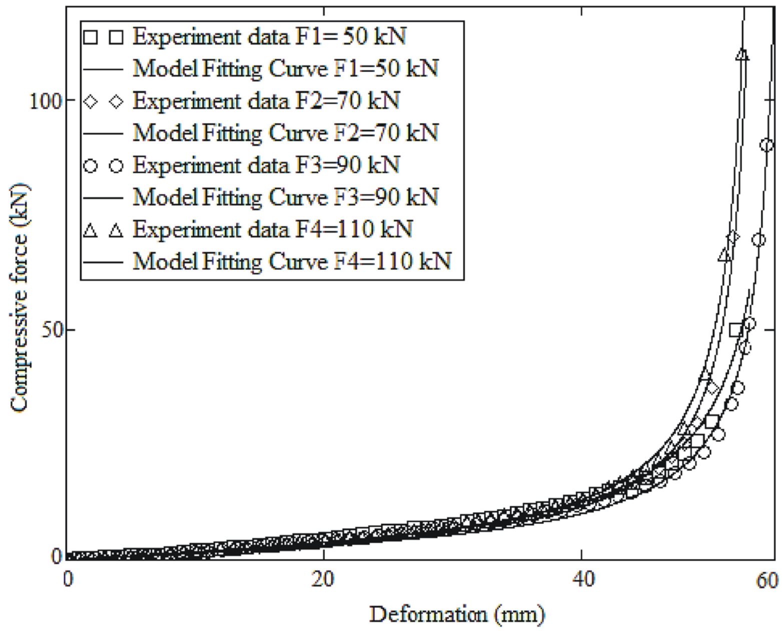

Fig. 2. Mechanical behaviour of sunflower bulk seeds at speed 10 mm min^{-1} fitted by the tangent curve model.

T a b l e 1. Determined coefficients of the tangent curve model and statistical analysis of sunflower bulk seeds (exponent of the deformation curve n = 1)

Force (kN)	Speed (mm min^{-1})	*A* (kN)	*B* (mm^{-1})	F_{ratio}	F_{crit}	p-value	R^2
50	10	6.283	0.028	0.030	3.934	0.862	0.988
70		5.083	0.029	0.031	3.934	0.861	0.994
90		5.044	0.028	0.035	3.934	0.852	0.996
110		5.662	0.029	0.005	3.934	0.945	0.997
50	50	5.271	0.029	0.008	3.934	0.927	0.998
70		4.942	0.029	0.014	3.934	0.907	0.998
90		5.500	0.031	0.003	3.934	0.957	0.996
110		5.860	0.030	0.001	3.934	0.997	0.995
50	100	5.159	0.031	0.002	3.934	0.961	0.999
70		5.070	0.031	0.006	3.934	0.937	0.999
90		5.681	0.310	0.005	3.934	0.998	0.998
110		6.692	0.030	0.011	3.934	0.917	0.987

A – force coefficient of the mechanical behaviour, *B* – deformation coefficient of the mechanical behaviour, F_{crit} is the critical value that compares a pair of models, F_{ratio} is the value of the F test, p-value is the significance level at which the hypothesis of equality of models can be rejected, R^2 is the measure of goodness of fit of the relationship between variables.

In this study, the optimal speed for higher oil recovery efficiency from sunflower bulk seeds using vessel diameter 60 mm and measured bulk seed height 80 mm was observed at the speed 10 mm min^{-1}, suggesting that maximum oil yield could be obtained at the lower speed. This hypothetical lower speed requires further verification in industrial technology involving mechanical screw presses to determine the efficient and economical speed for higher percentage oil from sunflower bulk seeds.

In compression loading, the vessel diameter and amount of compressive force also have an influence on oil yield (Divišová *et al.,* 2014). Therefore, in future research, there

T a b l e 2. Evaluation of force and speed on deformation, energy, and oil yield of sunflower bulk seeds (mean ± standard deviation)

Compressive force (kN)	Speed (mm min^{-1})	Deformation (mm)	Energy (MJ m^{-3})	Oil yield (g)
50	10	51.57±0.41	1.97±0.10	17.99±1.01
70		52.59±0.80	2.17±0.08	18.87±0.54
90		53.04±1.23	2.42±0.04	20.09±1.30
110		52.71±1.43	2.60±0.13	21.71±0.94
50	50	49.99±0.37	1.85±0.03	11.43±1.11
70		50.32±0.98	2.04±0.04	12.25±0.57
90		49.16±0.37	2.24±0.09	13.34±0.88
110		51.14±1.04	2.62±0.06	15.07±0.34
50	100	47.60±0.35	1.79±0.03	9.13±0.51
70		48.28±0.62	2.07±0.02	10.57±0.54
90		49.15±0.31	2.39±0.10	13.26±1.22
110		50.66±0.32	3.52±0.44	17.84±2.39

T a b l e 3. ANOVA Analysis of the varying effect of force on the measured data of sunflower bulk seeds at different speed

Measured data	Speed (mm min^{-1})	R^2	F-value	p-value
Deformation (mm)	10	0.29	1	>0.05
Energy (MJ m^{-3})		0.91	26	<0.05
Oil yield (g)		0.75	8	<0.05
Deformation (mm)	50	0.56	3	>0.05
Energy (MJ m^{-3})		0.97	83	<0.05
Oil yield (g)		0.82	12	<0.05
Deformation (mm)	100	0.91	30	<0.05
Energy (MJ m^{-3})		0.93	33	<0.05
Oil yield (g)		0.89	23	<0.05

Significant ($p < 0.05$), not significant ($p > 0.05$).

is a need to analyze the relationships between oil recovery efficiency, compressive force, and vessel diameter. Such factors as moisture content, bulk seed maturity, and genotype should be studied to fully understand the mechanical behaviour of bulk sunflower seeds.

The deformation value of 45 mm was denoted as the oil point as presented in (Fig. 3). The oil point value defines the minimum force required to cause oil flow from the bulk seeds. Compressive force and energy corresponding to the oil point strain of 0.56 were found to be approximately 16.65±3.51 kN and 1.06±0.18 MJ m^{-3}, respectively (Table 4). The energy value was observed to be higher than the literature value of 3.69±0.90 J (Rusinek *et al.,* 2012) and this difference could be due to the varying factors including bulk seed moisture content, volume of bulk seeds, force, speed, and vessel diameter.

Finally, the relationship between oil yield and oil point strain of sunflower bulk seeds was fitted by a linear trend as shown in (Fig. 4). However, the validity of this fitted function is limited only at the region of deformation characteristic curve with oil flow. Since only three points were obtained, the validity of the function is highly compromised.

T a b l e 4. Oil point detection of sunflower bulk seeds at speed 10 mm min^{-1} (mean ± standard deviation)

Deformation (mm)	Strain	Oil yield (g)	Force (kN)	Energy (MJ m^{-3})
30	0.38 ± 0.00	0.00 ± 0.00	6.25 ± 0.66	0.36 ± 0.06
35	0.44 ± 0.00	0.00 ± 0.00	7.89 ± 0.85	0.50 ± 0.06
40	0.50 ± 0.00	0.06 ± 1.07	9.79 ± 1.01	0.65 ± 0.07
45	0.56 ± 0.00*	8.02 ± 3.85	16.65 ± 3.51	1.06 ± 0.18

*Oil point strain of sunflower bulk seeds at pressing height 80 mm and vessel diameter 60 mm.

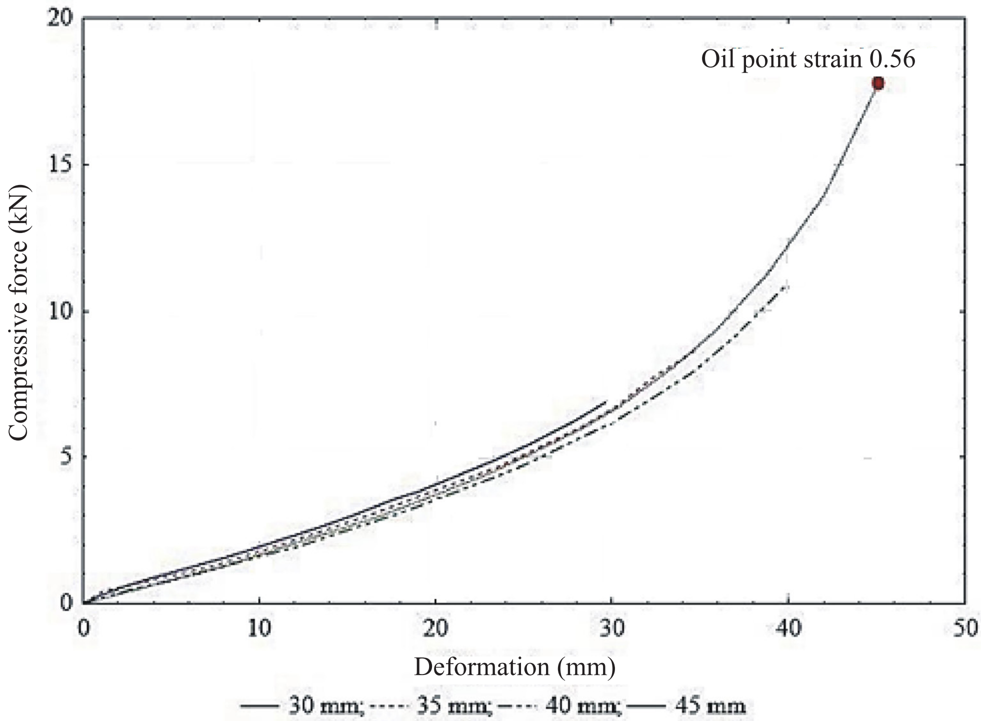

Fig. 3. Compressive force and deformation values for detection of oil point strain of sunflower bulk seeds at speed 10 mm min^{-1}.

CONCLUSIONS

1. Tangent curve model coefficients were determined for fitting the experimental dependence between compressive force and deformation curves of bulk sunflower seeds. The coefficients are valid for sunflower bulk seeds at pressing height 80 mm, vessel diameter 60 mm, forces between 50 and 110 kN, and speeds 10, 50, and 100 mm min^{-1}.

2. Energy and oil yield amounts were significant ($p<0.05$) at varying forces between 50 and 110 kN at constant speeds 10, 50, and 100 mm min^{-1}, respectively.

3. Deformation values were only significant ($p<0.05$) at speed 100 mm min^{-1}.

4. Optimal oil yield was observed at speed 10 mm min^{-1} and force 110 kN.

5. The oil point was noticed at deformation of 45 mm with a strain value of 0.56. The corresponding amounts of force and energy were 16.65±3.51 kN and 1.06±0.18 MJ m^{-3}, respectively.

6. Maximum force of 130 kN showed a serration effect on the force-deformation curves.

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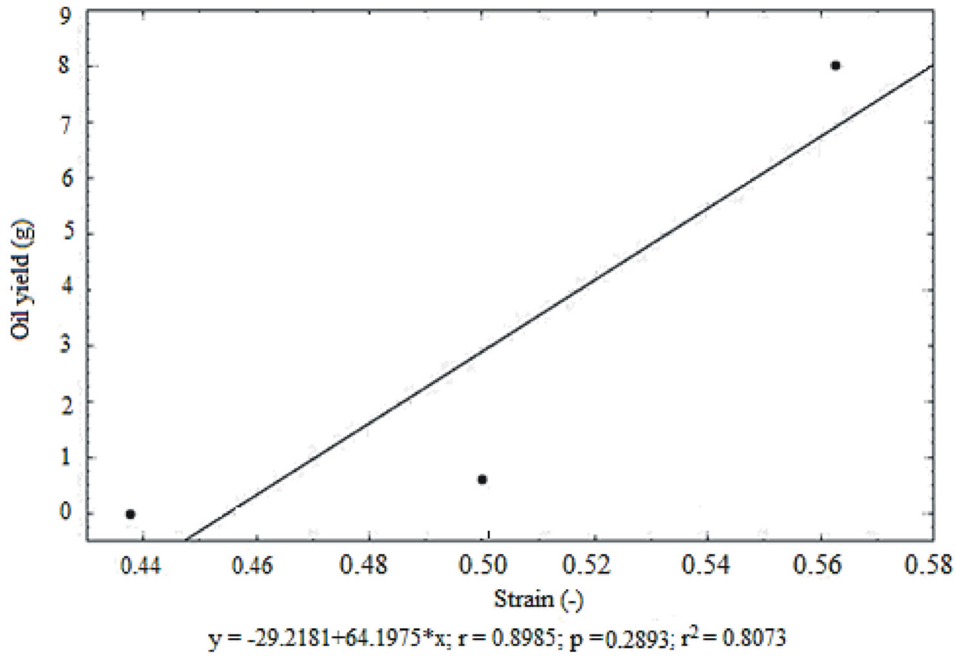

Fig. 4. Linear relationship between oil yield and strain of sunflower bulk seeds at speed 10 mm min^{-1}.

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