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Mechanical Pressing of Coconut Oil and Evaluation of Its Lubricant Properties

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Abstract: Vegetable oils represent an important element in protecting a sustainable environment. The pursuit of environmentally friendly solutions and the ever-increasing costs of synthetic oil production are increasing the interest in natural vegetable oils. This paper presents and discusses the possibilities of using the oils obtained from coconuts (*Cocos nucifera* L.) harvested in Indonesia (North Sumatra region), with three maturity levels (green, yellow, and brown), as lubricants. The specific mechanical energy for linear pressing of the green, yellow, and brown types was 22.3, 20.7, and 18.5 $J \cdot g_{oil}^{-1}$, respectively. The water content of the oils obtained from the green, yellow, and brown types was 1786, 2033, and 1902 mg $H_2O \cdot g^{-1}$, respectively. The mathematical models for linear pressing were established. The sizes of the wear area for the green, yellow, and brown types were 25.7, 24.4, and 34.3 mm^2, respectively. The UV–visible spectral curves of the oils, in the range of 180–320 nm, were determined. The results of the lubrication properties of the Reichert test showed that better lubrication properties were exhibited by the green and yellow types, which are comparable to the lubricating properties of engine oils. The results from the SEM images also showed a better structure of the worn surface and fewer traces of abrasive wear.

Keywords: specific mechanical energy; viscosity; friction; UV–vis spectroscopy; lubrication; coconut oil

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1. Introduction

Coconuts (*Cocos nucifera* L.) are well-known fruits in the tropical regions of Indonesia, Malaysia, India, Philippines, etc. These fruits are raw materials with multiple uses in food production, cosmetics, and chemistry.

Coconut oil, obtained by pressing the dried copra, contains fatty acids, mainly caprylic and capric [1,2]. There are four possibilities for extracting oil from oleaginous materials: extraction by mechanical methods (with mechanical presses and hydraulic presses), extraction by chemical methods (extraction with solvents and extraction with enzymes), extraction with supercritical fluids, and extraction by distillation [3–5]. Globally, due to advantages such as low equipment costs and the high quality of the obtained oils, mechanical pressing is the most commonly used method for extracting edible oils from oleaginous materials [6]. In addition, the mechanical pressing does not involve the use of additional solvents that contaminate the oil and the press cake. However, a drawback of mechanical pressing is its lower T (80%) compared with solvent extraction (98%) [7].

In recent years, the use of coconut oil for human consumption has visibly increased [8]. This is mainly because coconut oil is characterized by the content of vitamin E and many kinds of medium-chain triglycerides [9–11]. Lately, the use of natural oils in the field of industrial lubrication has also increased. Vegetable oils have very good lubricating properties and are biodegradable, so they can be a suitable alternative to mineral oils [12,13]. Most of the current lubricants contain petroleum substances, which are a burden on the environment and are difficult to be disposed of. Most used lubricants are lost in the environment. Therefore, it is necessary to look for alternative sources to produce lubricating oils. Vegetable oils have very low volatility and very good temperature–viscous properties. They also have very good adhesion to metal surfaces, which is a prerequisite for good lubricating properties [14]. In terms of disadvantages, they have very weak oxidation stability (mainly due to the content of bis-allylic protons, which results in an increase in oil acidity and viscosity), and low corrosion protection [15]. Today's lubricants are derived from petroleum, which has a negative impact on the environment. Regulation in the chemical industry and the ever-increasing environmental concerns have raised the interest in vegetable oil lubricants as a renewable resource.

The use of vegetable oils as lubricants will increase farmers' interest and improve their economic profits [16,17]. Vegetable oils have been used as a lubricant in the past, even before the discovery of petroleum [18]. Limited oil resources, pressure on the environment, and the increasing cost of synthetic oil production bring vegetable oils to the fore. Coconut oil is used most often in the lubrication of various agricultural machines and equipment.

A very important procedure for producing vegetable oils is quality control. In recent years, spectroscopic technology has been increasingly used to identify natural and synthetic oils. This is an analytical method to identify substances, their chemical composition, and their relative content. Spectroscopic technology (UV–visible) is very often used for the analysis of oils in the food industry and maintenance in the analysis of lubricating oils. It is a non-destructive method that is less time-consuming for sample preparation and data evaluation [19]. It is used for monitoring the presence of chlorophyll pigments and derivatives in natural oils. Study [20] focused on spectroscopic technology to evaluate the color index of transformer oil aging due to oxidation. The results showed a very strong dependence between the color index of the oils and the absorbance spectral responses of the oils in the visible wavelength (UV–vis). UV–visible spectroscopy is most used for monitoring oxidation in lubricating oils and biodiesel [21,22].

An important parameter when using coconuts is their maturity level, which affects a whole range of coconut properties. Premature coconuts have a very thin layer of coconut meat and more water. Mature coconuts are characterized by a stable layer of coconut meat and water. Conversely, over-mature coconuts have a very thick and hard layer of flesh that is almost water-free. The maturity level also affects the composition of the water of coconut milk and the physico-chemical properties of the nuts [23]. As the maturity level increases, the amount of water decreases, which partially turns into a jelly-like mixture inside the coconut [24]. It is therefore clear that the maturity level has a significant effect on the physico-chemical properties of coconuts, and subsequently on the pressed oils.

Some studies deal with the use of coconut oil as a lubricant, mainly from the point of view of adding various nanoparticles to improve their properties [5,9]. From the published studies, it was observed that the influence of the maturity level of coconuts on the lubricating properties of the obtained oils was not investigated. Thus, the effect of coconut maturity level on the change in lubricating properties has not been described.

This paper presents and discusses the possibilities of using the oils obtained from coconuts with three different maturity levels as industrial lubricants. The aim of this research was to determine the compressive forces, deformations, specific mechanical energy, and the mathematical models for linear pressing; the amount of oil obtained; as well as the water concentration, viscosity, lubrication properties, and UV–visible spectral curves of the obtained oils.

2. Materials and Methods

2.1. Coconuts

Coconuts (*Cocos nucifera* L.) divided into three categories according to their maturity level (green, yellow, and brown) and harvested in Indonesia (North Sumatra region) were used in this experiment. The coconuts were harvested in April, June, and October of the same year. For the individual categories, the maturity level corresponded to premature, mature, and over-mature fruits. Coconut water was removed from the harvested coconuts, and whole coconuts were halved to obtain coconut meat.

The coconut meat was ground into particles of the same homogeneous size using an electric grater. The prepared mixture was subsequently dried in a Memmert UN 55 dryer (Memmert GmbH + Co. KG, Schwabach, Germany) at a constant temperature of 35 ± 2 °C. The drying temperature was chosen so as not to affect the physico-chemical properties of the subsequently obtained oils. The final moisture content of the dried material was M_c = 7.0 ± 0.5% (w.b.). The moisture content of the material was determined by drying in an oven according to the ASAE S410.1 method [25]. The weight of each sample was weighed using an electronic balance (Kern FCB 30K1, Kern & Sohn GmbH, Balingen, Germany). The dried material, known as copra, was used in the experiments. Using a Soxhlet apparatus, the oil content of copra O_c (%) was determined. The extraction was carried out for 6 h at 60 °C using petrolether. Samples of 10 g of material for Soxhlet extraction were used.

2.2. Compression Tests

A compression device (MPTest 5.050, Labortech, Opava, Czech Republic) was used in the compression tests. Copra was pressed in a metallic pressing vessel (Figure 1) equipped with a press plunger, with a diameter of 60 mm and a height of 100 mm [26]. The holes in the bottom of the pressing vessel allow the easy draining of the pressed oil.

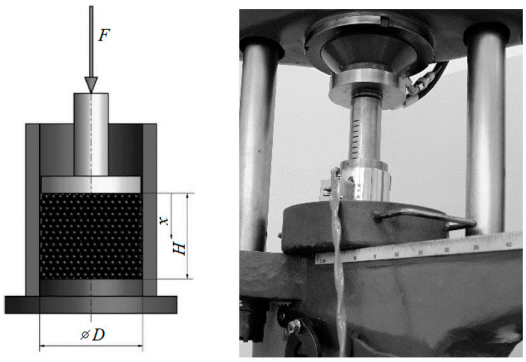

Figure 1. Schematic of a pressing vessel with a plunger diameter of 60 mm and the compression test.

The total weight of the pressed sample of copra was 100 g, which corresponds to a pressing height of 100 mm. This pressing height corresponds to the volume of the pressed sample of 28.275 × 10^{-5} m^3. All compression experiments were performed at the rate of 10 mm.min^{-1}, at room temperature of 21 ± 1 °C. The pressing forces ranged from 0 to 20 kN, values which are common for pressing natural materials [26]. A load of 20 kN corresponds to an equivalent pressure in the pressing vessel of 7.0735 MPa. For statistical evaluation, each pressing test was repeated six times.

A tangent function was used to fit the measured data. Data fitting was carried out in MathCad 14 software (PTC, Boston, MA, USA) using the genfit function, which uses the Levenberg–Marquardt algorithm for fitting functions [27,28]. Equation (1) can be used to express the dependence between the pressing force and the copra deformation [29].

$$F_x = A \cdot \tan(B \cdot x)^2 \quad (1)$$

where F_x—pressing force, N; A—constant, N; B—constant, mm^{-1}; x—copra deformation, mm.

The area under the compressive force–deformation curve is expressed as deformation energy and was calculated using Equation (2) [30].

$$E_x = \sum_{n=0}^{n=i-1} \left[\left(\frac{F_{n+1} + F_n}{2} \right) \cdot (X_{n+1} - X_n) \right] \quad (2)$$

where E_x—deformation energy, J; F_{n+1} and F_n—values of compressive force, N; X_{n+1} and X_n—values of deformation, m.

The oil yield of copra was calculated using Equation (3) [31].

$$O_\gamma(\%) = 100 \cdot \left[\frac{O_w}{O_m} \right] \quad (3)$$

where O_γ—percentage oil yield (%); O_w—mass of oil, g; O_m—mass of initial height, g.

Subsequently, the specific mechanical energy was determined as the ratio of deformation energy and total oil yield.

2.3. Analysis of Lubrication Properties

A WDT coulometer was used as standard to measure the water content of tested oil samples. The coulometric method enables the detection of small or even trace amounts of water in various solutions. Detection can be performed in solutions based on organic acids, hydrocarbons, alcohols, esters, and many other organic solvents. The Stabinger Viscometer was used to determine oil viscosity at 40 °C and 100 °C. This analyzer has similar precision to a gravimetric capillary viscometer and covers a wide measurement range with a single measuring cell. Each sample of oil was measured three times for water content and five times for viscosities. The friction was determined with the Reichert tester M2 (Figure 2), which belongs to a group of machines that simulate real friction.

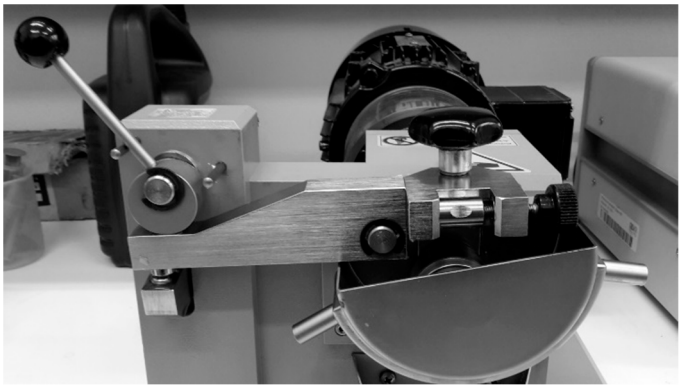

Figure 2. Reichert Friction and Wear Tester with used test roller.

The frictional contact was evaluated based on the bearing capacity of the lubricating film, which was in accordance with the standards [32] of the Petrotest company. The measurement was based on the principle of a test roller, which was tightly clamped and pushed by a weight onto a rotating collection ring (made of alloy steel) by a lever mechanism for a defined distance. The ring was partially immersed in the oil bath. During the measurement, a sufficient amount of tested oil was fed into contact between the test cylinder and the collector ring. Each test was repeated six times for statistical evaluation.

The lubricity of the tested oil was determined according to the size of the elliptical surface on the test cylinder [33]. The smaller the size of the wear area on the cylinder, the

better the lubricating properties of the oil. Equation 4 was used to calculate the elliptical surface [34].

$$A = \pi \cdot \frac{l}{2} \cdot \frac{d}{2} = 0.785 \cdot l \cdot d \quad (4)$$

where A—elliptical wear area, mm^2; l—length of elliptical wear area, mm; d—width of elliptical wear area, mm.

For a better understanding of the lubricity, the load-carrying capacity was evaluated using Equation (5).

$$U = \frac{2000 \cdot G \cdot 9.81}{A} \quad (5)$$

where U—load-carrying capacity, $N.cm^{-2}$; G—weight of load (1.5 kg); A—elliptical wear area, mm^2.

The conditions under which the Reichert test was performed are presented in Table 1.

Table 1. Conditions of Reichert test.

Load	1.5 kg
Test duration	100 m
Sliding speed	1.7 $m \cdot s^{-1}$
Sample volume	25 mL
Temperature	22 °C
Roll material	steel, Petrotest 150021
Ring material	steel, Petrotest 150023

The device measures the length l and width d of the elliptical wear surface A, which evaluates the bearing capacity of the lubricating film and then indicates the accuracy and range of the measurement. As a reference, motor oil with performance classification API SN/CF, ACEA A3/B3 and viscosity specification 5W–40 was used. A four-ball tribometer was used to determine the friction torque and to calculate the friction coefficient. The test was performed according to the ASTM D 5183-05 standard [35], at a speed of 600 rpm and a load of 40 kg.

2.4. Analysis of the Wear Surface Using an Electron Microscope

Wear area after the Reichert test was studied using a scanning electron microscope (Tescan Mira3, Czech Republic). The observation was prepared in the secondary electron mode with an accelerating voltage of 10 kV.

2.5. Determination of UV Spectral Parameters

The obtained coconut oils for different types of maturity level were analyzed using the spectrophotometer VIS UV-21 (SpektrometrOnda, Carpi, Italy). The absorbance of the obtained oil samples for different wavelengths was determined. Individual oil samples were placed in UV transparent quartz sampling cuvettes with dimensions of 10 × 10 × 30 mm. Absorbance characteristics were determined using a single-beam UV spectrophotometer. The measurement was carried out at a wavelength of 325–600 nm. Distilled water was used as a reference value to determine the absorbance. After the measurement, each quartz cuvette was cleaned with alcohol, and the measurement was repeated one by one.

3. Results

The physical parameters of copra such as moisture content M_c = 6.9 ± 0.5% (w.b.) and particle size P_s = 3.2 ± 0.3 mm were constant. The oil content of copra O_c was 61.3, 65.7, and 66.8% for the green, yellow, and brown type, respectively. The measured values of single pressing curves for the different types of coconut are shown in Figure 3. The measured values of pressing force and deformation for the individual types of coconuts were fitted using a tangent curve.

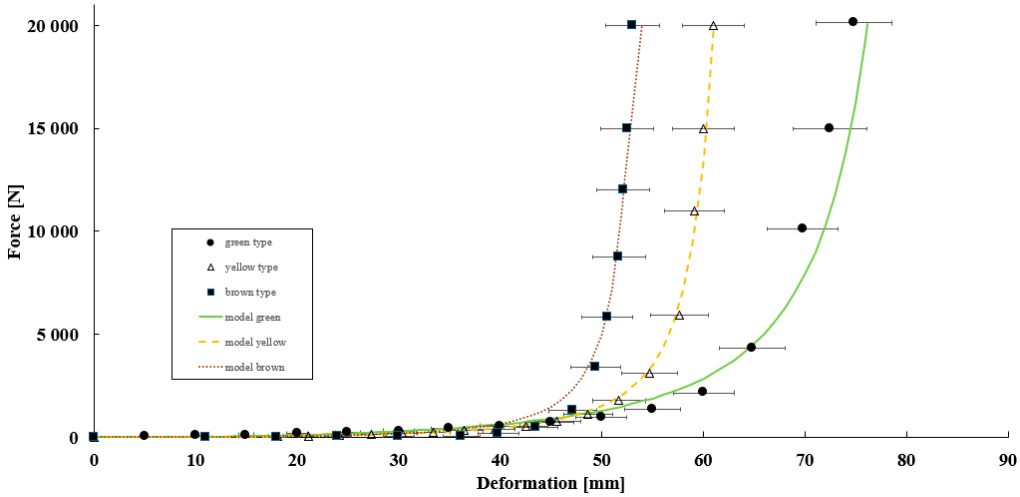

Figure 3. Measured values and fitted model for different types of coconuts with displayed amounts of coefficients of variation.

The function is described by Equation (1), and the individual coefficients of the equation are listed in Table 2.

Table 2. Calculated coefficients of the mechanical pressing model for different types of coconut and their statistical analysis.

Type	A (N)	B (m^{-1})	F_{rat} (-)	F_{crit} (-)	P_{value} (-)	R^2 (-)
Green	816	0.018	2.72×10^{-3}	4.13	0.959	0.992
Yellow	230	0.024	5.65×10^{-3}	4.13	0.981	0.998
Brown	154	0.028	4.99×10^{-3}	4.196	0.944	0.995

The coefficients of the equation were determined in MathCad 14 software (PTC, USA) using the genfit function, which uses the Levenberg–Marquardt algorithm [27,28]. A very strong dependence between the measured values and the proposed model (Equation (1)) is shown by the statistical analysis ANOVA (analysis of variance), which proves the suitability of using the tangent function for data fitting. The measured values of compressive force for the different types of coconuts and results from the tangent model (Equation (1)) were statistically significant at the level of significance of 0.05. This means that F_{crit} values (specific value comparing two models) were higher than F_{rat} values (F—test value), and *p*-values (significance level at which the hypothesis of equality of models can be rejected) were higher than 0.05 (Table 2). This is also confirmed by the very high value of the coefficient of determination R^2. The deformation energy was calculated using Equation (2) and is 230, 190, and 180 J for the green, yellow, and brown type, respectively. The measured values of deformation energy are significantly lower than those of other types of oilseeds [36]. Based on the calculated energy and the obtained oil, the specific mechanical energy was determined, and its values are shown in Figure 4.

In terms of the energy consumption of oil pressing, the most suitable variant is the brown type, which achieved a 17.4% lower specific energy per gram of obtained oil compared with the other types. Similar values were also measured by the authors of [26], who studied the energy intensity of coconut oil pressing. The oil yield was calculated using Equation (3) and is 0.192, 0.224, and 0.247 for the green, yellow, and brown type, respectively. Regarding the chemical and lubrication properties, one of the parameters that has been calculated is the water concentration, which is shown in Figure 5.

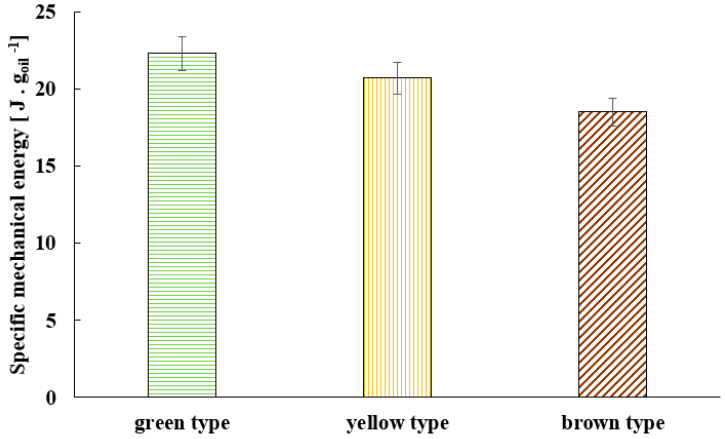

Figure 4. Energy consumption per gram of oil obtained from different types of coconut.

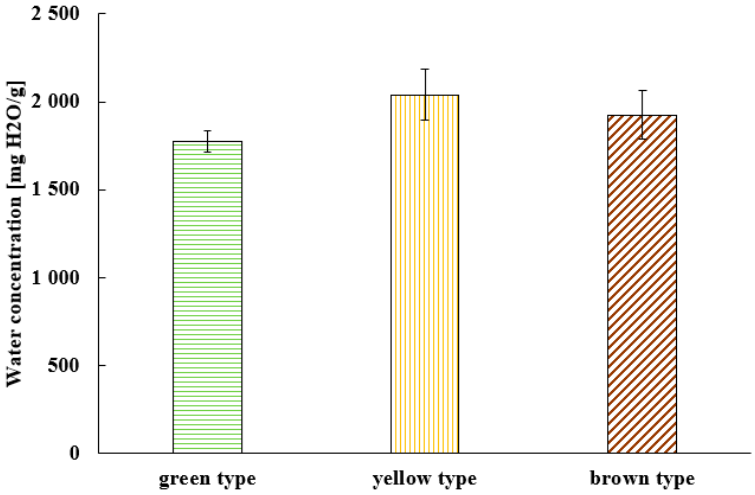

Figure 5. Water concentration in the obtained oils.

From Figure 5, it is obvious that the green type has a slightly lower concentration of water than the yellow type. The water content also affects the viscosity value. A lower viscosity value was measured for the yellow type, as presented in Table 3.

Table 3. Viscosity properties of obtained oils; data in the table are means ± SD.

Type	Dynamic Viscosity at 40 °C (mPa·s)	Kinematic Viscosity at 40 °C ($mm^2 \cdot s^{-1}$)	Dynamic Viscosity at 100 °C (mPa·s)	Kinematic Viscosity at 100 °C ($mm^2 \cdot s^{-1}$)
Green	25.7380 ± 0.0609	28.2420 ± 0.0694	5.3370 ± 0.0391	6.1450 ± 0.0478
Yellow	24.7970 ± 0.0323	27.1880 ± 0.0250	5.0950 ± 0.0063	5.8590 ± 0.0058
Brown	25.1030 ± 0.0466	27.4420 ± 0.0519	5.6430 ± 0.0193	6.4970 ± 0.0217
Motor oil SAE 5W-40	76.5510 ± 0.0914	90.9030 ± 0.1770	11.6190 ± 0.0153	14.4430 ± 0.0182

Viscosity is the basic property of a machine lubricant. It expresses the degree of resistance to flow. It is evident from the measured values that the individual types of coconut oils show comparable viscosity values. No significant influence of the maturity level of the coconuts on the change in the dynamic and kinematic viscosity of the obtained oils was found. With oils that have a very low viscosity, there is a possibility of metal-to-metal contact between machine parts. This is due to the very thin layer of lubricating film in low-viscosity oil. On the other hand, oils with a high viscosity may stop the flow of lubricating oil and thus reduce the lubrication effect. The lower viscosity of the

yellow type is partially due to its higher content of water. The measured values of the kinematic viscosity of virgin coconut oil (27.5 ± 0.5 mm^2/s) are comparable to the published results of other authors [37,38]. Study [13] reported a kinematic viscosity of coconut oil of 27.82 mm^2/s at a temperature of 40 °C, and 7.07 mm^2/s at a temperature of 100 °C. Oil viscosity decreases with increasing temperature due to the momentum in the fluid molecules. The speed of oil molecules increases with increasing temperature, which causes the intermolecular force between the molecules to decrease and thus the viscosity of the oil to decrease [39,40]. The myristic and lauric acid content of coconut oil also causes a thick lubricating oil film [41,42]. Coconut oil has a lower kinematic viscosity value compared with other natural oils, such as rapeseed (45.6 mm^2/s [43]), mustard (44.1 $mm^2.s^{-1}$ [44]), and jatropha (35.4 mm^2/s [45]). In general, the viscosity of natural oils is lower than that of industrial oils. In terms of molecular weight, the natural oils achieve higher consistency than mineral oils, and therefore they also have a higher viscosity index [44]. The measured values of oil density are presented in Table 4.

Table 4. Density and coefficient of friction of obtained oils and motor oil; data in the table are means ± SD.

Type	Density at 40 °C ($g \cdot cm^{-3}$)	Density at 100 °C ($g \cdot cm^{-3}$)	Coefficient of Friction (-)
Green	0.9100 ± 0.0004	0.8690 ± 0.0009	0.0823 ± 0.0012
Yellow	0.9150 ± 0.0021	0.8690 ± 0.0012	0.0871 ± 0.0023
Brown	0.9120 ± 0.0003	0.8700 ± 0.0004	0.0937 ± 0.0039
Motor oil SAE 5W-40	0.8420 ± 0.0008	0.8050 ± 0.0011	0.1066 ± 0.0044

It is clear from the measured density values of the individual coconut oils that there are no significant differences. Other natural oils reach a similar density value, which is a basic prerequisite for easy homogeneous mixing [10].

According to study [41], the carbon chains of vegetable oils and unsaturated fatty acids provide a stable lubricating film layer comparable to mineral oils. These findings also correspond with the results of the Reichert test.

The results of the Reichert tester measurements (Figure 6) show that the lubrication properties of the green and yellow types are similar to those of the sample of motor oil. On the other hand, the brown type shows a larger area of friction wear.

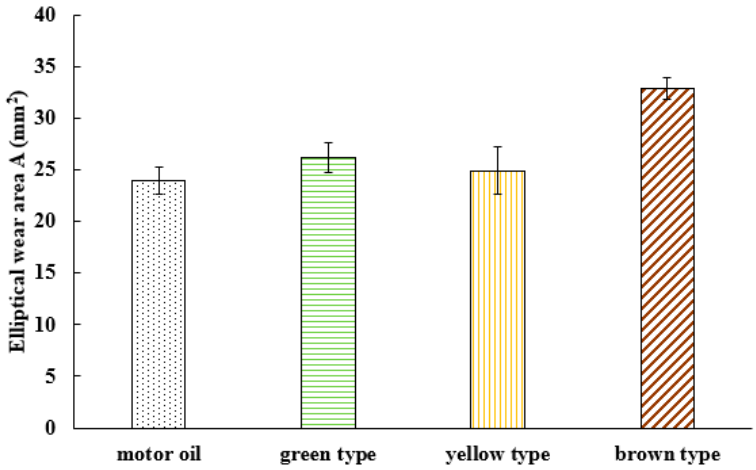

Figure 6. Elliptical wear area A with standard deviation.

The authors of study [42] focused on testing the lubricating properties of oils pressed from jatropha seeds. Jatropha oil shows better lubricating properties, i.e., a smaller wear area than that of coconut oils. The size of the wear area of the Reichert test was around

19.5 mm^2 in the case of jatropha oil. In study [16], a similar experiment was conducted concerning a comparison of different samples of coconut, including measurements of lubrication properties with the four-ball test. The experiment yielded similar results. Study [9] compared the lubricating properties of coconut oil and mineral oil. A lower coefficient of friction and better oxidation properties were found for coconut oil. In general, the natural oils can be used as boundary lubricants because, due to their high polarity, they have a high affinity for lubricated surfaces. The lubricating properties of the oil are influenced by the ability of its molecules to attract the surface lattice of the metal and subsequently to react with it [46]. Similar friction coefficient results for coconut oil were also found by other authors [9].

The load-carrying capacity was evaluated using Equation 5, and its values were 1145, 1206, and 858 $N.cm^{-2}$ for the green, yellow, and brown type, respectively. Friction coefficient values were determined using a four-ball testing machine and are shown in Table 4. Friction coefficient values are affected by free fatty acids and their carbon chain length [47]. Coconut oil consists of fatty acids with a shorter carbon chain length and thus exhibits higher friction coefficient values than do other natural oils [48]. Higher values of the coefficient of friction were determined for the brown type of coconut. The lowest values of the coefficient of friction (0.0823 ± 0.0012) were determined in the green type. Study [39] reported a coefficient of friction value for sunflower oil that was significantly lower than for coconut oil. In general, coconut oil is a very good lubricant in terms of its friction coefficient. However, it has a higher wear rate than commercial lubricants. The use of coconut oil as a lubricant is also limited by other issues, such as oxidation stability and properties at low temperatures, especially the pour point.

The worn surface of the pin after the Reichert test was analyzed using scanning electron microscopy (SEM), which is shown in Figure 7. The images show different pins for different types of lubricants.

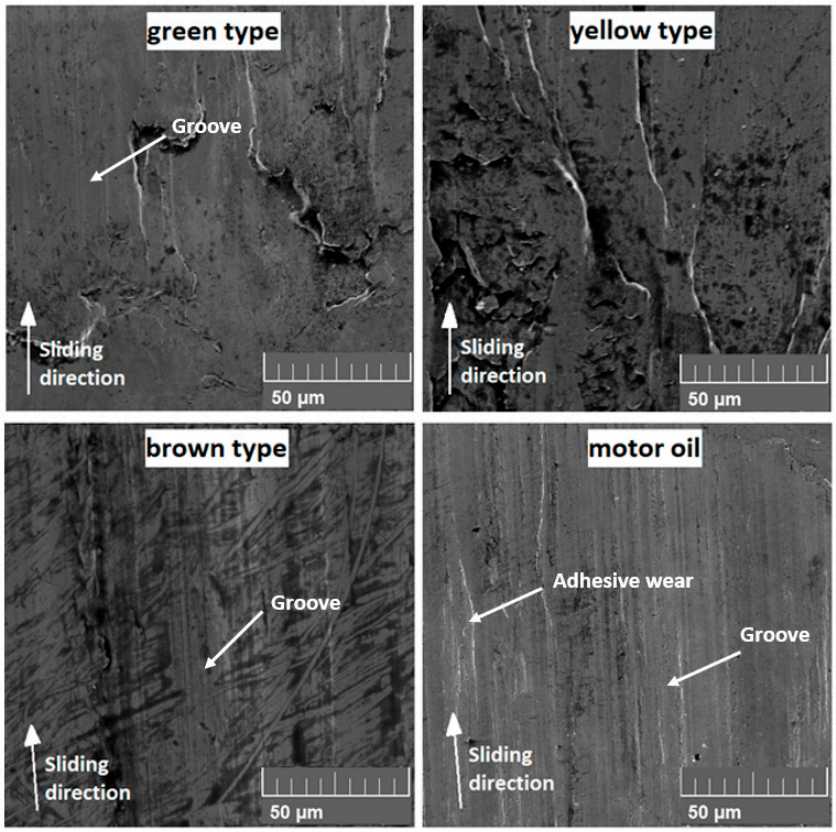

Figure 7. SEM images of the pin after Reichert test for different types of coconut oil and motor oil.

Individual images show the presence of adhesive wear. Only the motor oil variant shows small areas of adhesive wear. The picture shows a groove parallel to the sliding wear direction, which is an indication of abrasive wear. The presence of grooves is visible especially in the brown type. In this case, deep grooves in the sliding direction are visible. In contrast, almost no grooves are visible in the green and yellow types. It is therefore possible to conclude that the green and yellow types have lower abrasive wear than the brown type. The green and yellow types show similar results to those reported in study [42] for jatropha and moringa oil. The individual images show a similar type of wear at a 60 μm scan scale for jatropha and moringa oil.

The measured absorbance values of the individual types of coconut oils in the wavelength range of 325–600 nm are shown in Figure 8. The indicated wavelength represents the UV–visible absorption spectrum. The spectra showed a wide level of variation with predominant peaks at 355 and 425 nm. The measured curves for the individual types of coconut oil show similar absorbance values and the same peak band. A very strong absorption peak at 350 nm is seen in all types of oils and is probably due to chlorophyll and carotenoid pigments [49]. Two absorbance peaks in the 325–600 nm wavelength band are typical for coconut oil. Similar curves are reported by other authors for virgin coconut oil [50].

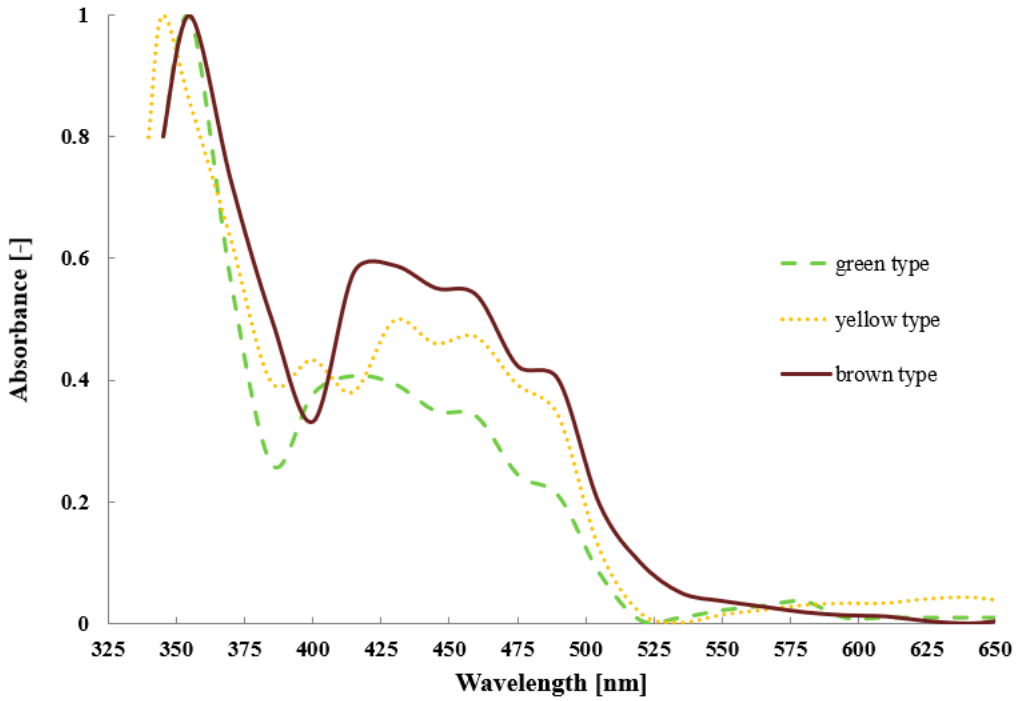

Figure 8. The absorption of oil obtained from different types of coconut.

4. Conclusions

The specific mechanical energy for linear pressing of the green, yellow, and brown types of coconut was 22.3, 20.7, and 18.5 $J \cdot g_{oil}^{-1}$, respectively. The compressive curves were fitted using a tangent equation, and the coefficients were determined. The proposed model of coconut pressing curves was statistically analyzed. The lowest oil viscosity values were measured for the yellow type. The sizes of the wear areas for the yellow and green types were 25.7 and 24.4 mm^2, respectively, and reached the same values as for motor oil. Significantly higher wear was recorded for the brown type of coconut with a wear area of 34.3 mm^2. From the measured results, it can be concluded that the green and yellow coconuts had better lubricating properties than the brown type. Future studies could focus on the oxidative stability of the obtained oils using FT-IR spectroscopy. Another goal of future research could be to focus on corrosion protection, which is generally a problem

when using natural oils as lubricants. The issue of the pour point of coconut oil when used in industrial applications also needs to be investigated in the future. Since coconut oil is more environmentally friendly than mineral oils, it makes sense to continue research into the use of coconut oil as an industrial lubricant.

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