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Nondestructive Prediction of Oil Palm Fruit Quality During Processing Delays Using Electrical Impedance Spectroscopy

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ABSTRACT

Nondestructive prediction of palm fruit quality is needed to monitor changes in palm fruit quality during processing delays. This study aims to develop a method for predicting the chemical quality of palm fruit during processing delays using the Electrical Impedance Spectroscopy (EIS). The electrical impedance of palm fruit were measured at frequencies of 50 Hz to 1 MHz and followed by the determination of free fatty acid (FFA) and moisture content using chemical methods. The best initial treatment for impedance spectrum data in this study was Standard Normal Variate (SNV) and Baseline. The results of this study indicate that the PLS method outperforms PCR in predicting FFA and moisture content. The best prediction for free fatty acid content was using the SNV pre-treatment and component factor 7 with a value of r = 0.87; SEC = 2.75%; SEP = 2.82%; CV = 23.81%; RPD = 1.94 and consistency of 97.75%. The best prediction for moisture content was obtained using the Baseline initial treatment and component factor 15 with a value of r = 0.97; SEC = 3.65%; SEP = 3.82%; CV = 28.24%; RPD = 1.91 and consistency of 83.24%. The developed electrical impedance and PLS methods can be used to predict free fatty acid content and moisture content of oil palm fruit during processing delays.

1. INTRODUCTION

The palm oil industry contributes a large amount of foreign exchange to the country's development with a growth of 10.13% over the last three decades (Nayantakaningtyas & Daryanto, 2012). After harvesting, the oil content of palm fruit will not increase, so errors in determining the ripeness of fresh fruit bunches will result in low oil yields and a decline in palm oil company revenues (Basyuni *et al*., 2025). Excess ALB causes damage and rancidity of the oil produced (Iqbal *et al*., 2014). This problem is very detrimental to oil palm plantation companies and oil palm farmers. Therefore, after harvesting, palm fruits must be processed immediately considering that palm fruits will experience a decline in quality within 8 to 24 h after harvest (Hudori, 2011).

To date, the method for determining the chemical content of palm fruit has been carried out conventionally in laboratories (Akbar *et al*., 2023). Another method that is widely practiced is chemical testing in the laboratory (Makky & Soni, 2014). This method is expensive, destructive, and takes a long time to determine the results.

One of the nondestructive methods that can detect changes in the chemical properties of oil palm fruit after harvesting is by using electrical impedance spectroscopy (EIS). Research on the electrical properties of oil palm fruit has been widely conducted such as research conducted by Harun *et al*. (2013), which determines two levels of palm fruit maturity at a frequency of 100 Hz to 100 MHz, by Aliteh *et al*. (2018) developed an electrical sensor to detect

palm fruit maturity. In addition, research conducted by Mellyana *et al*. (2024) using electrical properties can predict chemical content at ten levels of harvest age. Although previous studies have attempted to determine the quality of oil palm fruit, many of them still focus on the condition of the fruit at harvest or use conventional methods such as chemical analysis in laboratories. These methods are not efficient for monitoring rapid changes in quality that occur during post-harvest delays, such as those experienced by fruit during transport or temporary storage. Therefore, this study offers a novel approach by developing a non-destructive prediction method based on Electrical Impedance Spectroscopy (EIS). The aim is to develop a method that can predict the chemical properties of palm fruit after harvest non-destructively using electrical impedance spectroscopy (EIS) with PLS and PCR methods.

2. MATERIALS AND METHODS

2.1. Tools and Materials

The tools used in this study consisted of an LCR meter (Hitester 3532–50, Hioki E.E. Corporation, Japan), a conductor plate made of copper, and a cold storage unit with temperatures of 5 °C and 10 °C. Other tools included an aluminum cup, desiccator, oven at 105 °C, Erlenmeyer flask, burette, measuring cup, and volumetric flask. The materials used in this study were palm fruit aged 5 months and 2 weeks, CO_2-free distilled water, sodium hydroxide (NaOH), neutral 95% ethanol, 0.5% phenolphthalein indicator solution in 95% ethanol, and 95% ethanol mixed solvent. Data were processed using Microsoft Excel and The Unscrambler X 10.4, where calibration and validation processes used the Partial Least Squares (PLS) and Principal Component Regression (PCR) methods.

2.2. Sample Preparation

The samples were oil palm fruits with an optimal harvest age of 5 months and 2 weeks. A total of 81 oil palm fruit samples were taken and stored at 5 °C, 10 °C, and room temperature for three days of processing delays. Data were taken every 8 h during processing delays.

2.3. Measurement of Electrical Properties

Measurement of the electrical impedance properties of oil palm fruits was carried out based on the method conducted by Mellyana *et al*. (2025) with the LCR meter Hitester 3532-50 Hioki, Tokyo, Japan (Hioki Corporation, 2015) at a frequency of 50 Hz−1MHz. The fruit was placed between two electrode plates and the impedance value was measured. The signal voltage was kept constant at 1 Voltrms.

2.4. Measurement of Chemical Properties

2.4.1. Moisture Content

Moisture content was measured using the oven method according to SNI 01-3555-1998. The equipment and tool included analytical oven, balance, desiccator, and aluminum cups. The oven was set at a temperature of 101±1 °C. The moisture content of each fruit was computed from initial weight (a) and final weight (b) using Equation 1.

$$\text{Moisture content (\%)} = \frac{a-b}{a} \times 100 \quad (1)$$

2.4.2. Free Fatty Acid Content (FFA)

The acid value denotes the number of NaOH (mg) required to neutralize the one gram FFA in the oil or fat. A higher acid values indicate higher FFA content and the lower quality of oil. The high acid number could potentially originated from oil hydrolysis or insufficient processing. Measurement of free fatty acid (FFA) content used the titration method based on SNI 01-3555-1998. The data obtained was then calculated using equation 2.

$$\text{FFA (\%)} = \frac{M \times V \times T}{10 \times m} \times 100 \quad (2)$$

where M is the molecular weight of free fatty acids (g), V is the volume of NaOH required in the titrant (ml), T is the normality of NaOH, m is the weight of the sample (g).

2.5. Pre-treatment

Before calibration, several pre-treatments are applied such as Normalization (N), Standard Normal Variate (SNV), Multiplicative Scatter Correction (MSC), and Baseline. Pre-treatment was done to obtain accurate and stable calibration results due to spectra that still contain noises (Cen & He, 2007).

2.6. Calibration and Validation

The data obtained consisted of 81 nondestructive measurement data (electrical impedance data) and destructive measurement data (chemical data). The amount of data used in the calibration group was 2/3 of the total data and validation was 1/3 of the total data, namely 54 data for calibration and 27 data for validation. The data was collected and then processed using The Unscrambler® X 10.4, which produced the best calibration form and model between the impedance data and the destructive test results using the Partial Least Squares (PLS) and Principal Component Regression (PCR) methods. The formulation to estimate the FFA content was presented in Equation (3).

$$\text{FFA (\%)} = \beta + \beta_1 f_1 + \beta_2 f_2 + \beta_3 f_3 + \ldots + \beta_n f_n \quad (3)$$

where β was constant, β_n was coefficient of n^{th} predictor, and f_n was the pre-treated spectra values of the n^{th} predictor at specific frequencies. The formulation to estimate the moisture content (MC) was articulated in Equation (4).

$$\text{MC (\%)} = \alpha + \alpha_1 f_1 + \alpha_2 f_2 + \alpha_3 f_3 + \ldots + \alpha_n f_n \quad (4)$$

where α was constant, α_n was coefficient of nth predictor, and f_n was the pretreated spectra value of the nth predictor at specific frequencies.

The results of PCR and PLS calibration and validation were evaluated based on the coefficient of determination (R^2), calibration standard error (SEC), validation standard error (SEP), CV, RPD, and consistency. A good model has statistical parameters with r values close to 1, small SEP, SEC, and CV values close to 0, and RPD values > 1.5 which indicates a fairly good prediction of model accuracy and consistency between 80–110% (Nicolai *et al*., 2007).

3. RESULTS AND DISCUSSION

3.1. Oil Palm Fruit Impedance

Electrical impedance measurements for three storage temperatures are shown in Figure 1. Overall, the impedance value of palm fruit decreases as the frequency increases. The impedance value of palm fruit during the delay period continues to decrease significantly from a frequency of 50 Hz to 3 kHz and tends to stabilize at frequencies from 30 kHz to 1 MHz. The phenomenon of a significant decrease in impedance with increasing frequency occurs due to the interaction of electric current with the cell structure. At low frequencies, the cell membrane acts as an insulator, forcing the current to flow through extracellular pathways that have high resistance, resulting in high overall impedance. The

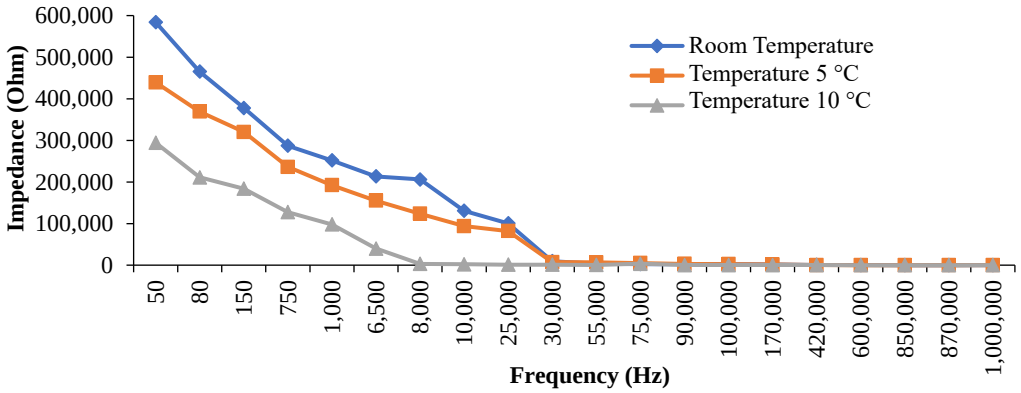

Figure 1. Impedance graph of oil palm fruits during processing delays

phenomenon of impedance decrease due to frequency increase has also been reported by Wu *et al*. (2008) in eggplants, Vozáry & Benkő (2010) in apples, and Juansah *et al*. (2014) in citrus fruits. Impedance in capacitor chip circuits is influenced by frequency, resistance, and total reactance (Tipler, 2001).

3.2. FFA Content

Changes in free fatty acid (FFA) content after a 60-h delay can be seen in Figure 2a. Before the delay, the palm fruit still met the CPO standard of below 5%. However, after a 6-h delay, palm fruit at 5 °C and 10 °C still met CPO quality standards. After a 12-h delay, only palm fruit at 5 °C still met CPO quality standards, with an FFA content below 5%. After a delay of more than 12 h, the FFA content of the palm fruit was above 5%, meaning it did not meet the CPO quality standard. The relationship between temperature and the rate of FFA formation shows that temperature is the main factor controlling lipase enzyme activity. At room temperature, the enzyme works optimally, causing hydrolysis to proceed very quickly and resulting in a sharp increase in FFA. Conversely, at cold temperatures (5 °C and 10 °C), enzyme activity slows down significantly. These cold conditions effectively inhibit the enzymatic process, resulting in a much lower rate of FFA formation. The higher the FFA content, the lower the quality of the oil produced (Paramitha & Ekawati, 2022).

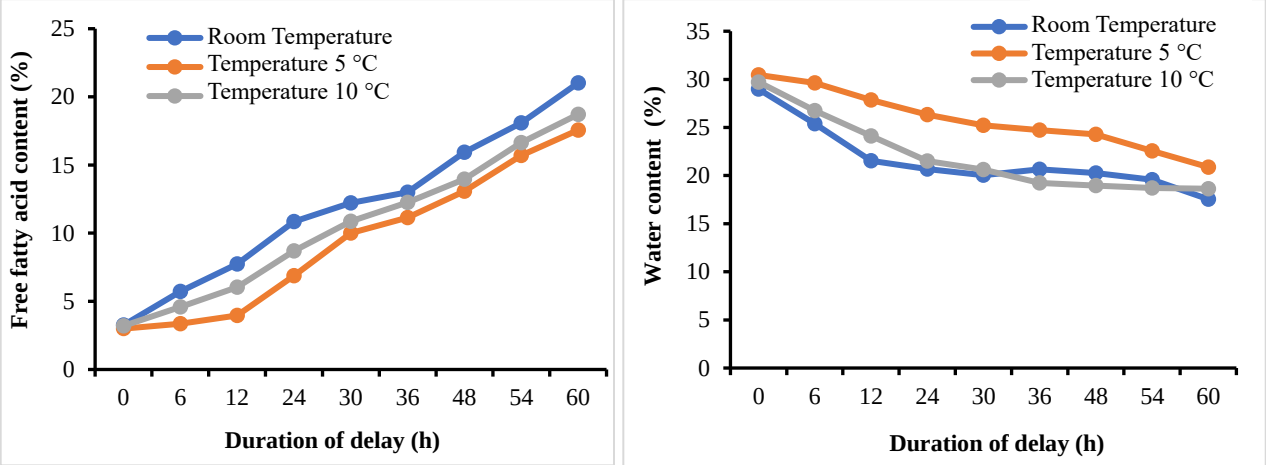

Figure 2. Effect of temperature and delaying time on the properties of oil palm fruits: (a) Free fatty acid, (b) moisture content

3.3. Moisture Content

Overall, the highest water content was found at a temperature of 5 °C with a value of 31.25%, while the lowest water content was found at room temperature with a value of 17.14%. From the graph in Figure 2b, it can be seen that the decrease in water content at temperatures of 5 °C and 10 °C tends to be slower than the delay in oil palm fruit at room temperature. Physiologically, cold temperatures slow down all metabolic processes, including transpiration. Vapour pressure at lower temperatures becomes smaller, reducing the gradient between the palm fruit and the air. This reduces the rate of water loss, which has been proven effective in maintaining the weight and water content of the fruit.

3.4. Calibration and Validation with PLS Method

3.4.1. FFA Content

The results of data processing to predict ALB content using the PLS method are presented in Table 1, while the data distribution graph of the calibration and validation results for palm fruit ALB prediction using the PLS method with SNV 7-factor data processing can be seen in Figure 3a. The best prediction for the fatty acid content parameter was obtained from the SNV pre-treatment on the 7th PLS factor. This model has a coefficient of determination (R^2) of 0.75, SEC and SEP values of 2.75% and 2.82%, respectively. The RPD value obtained was 1.94, with a consistency of 97.75% and a Coefficient of Variation (CV) of 23.81%. Although the R^2 value indicates a fairly good correlation, an

RPD value of less than 2 indicates that this model is still in the moderate prediction category. This shows that although the model can be used for initial estimates, its accuracy may not be sufficient for industrial applications that require high precision. In addition, the high CV value —which, according to Pamungkas *et al*. (2014), indicates a high level of data heterogeneity— suggests that the sample data have large variations. The implication is that the model may be less reliable when applied to palm fruit samples with highly diverse conditions.

Table 1. Data processing results of free fatty acid content with PLS method

Treatment	Factor	Calibration Set		Validation Set			Consistency
		R^2	SEC (%)	SEP (5%)	CV (%)	RPD	
Original	7	0.72	2.91	3.17	26.78	1.71	91.61%
Normalisasi	9	0.81	2.14	2.99	25.28	1.81	81.57%
Baseline	8	0.77	2.61	3.01	25.48	1.81	86.69%
Standard Normal Variate	**7**	**0.75**	**2.75**	**2.82**	**23.81**	**1.94**	**97.75%**
Multiplicative Scatter Correction	8	0.72	2.92	3.28	27.74	1.65	88.96%

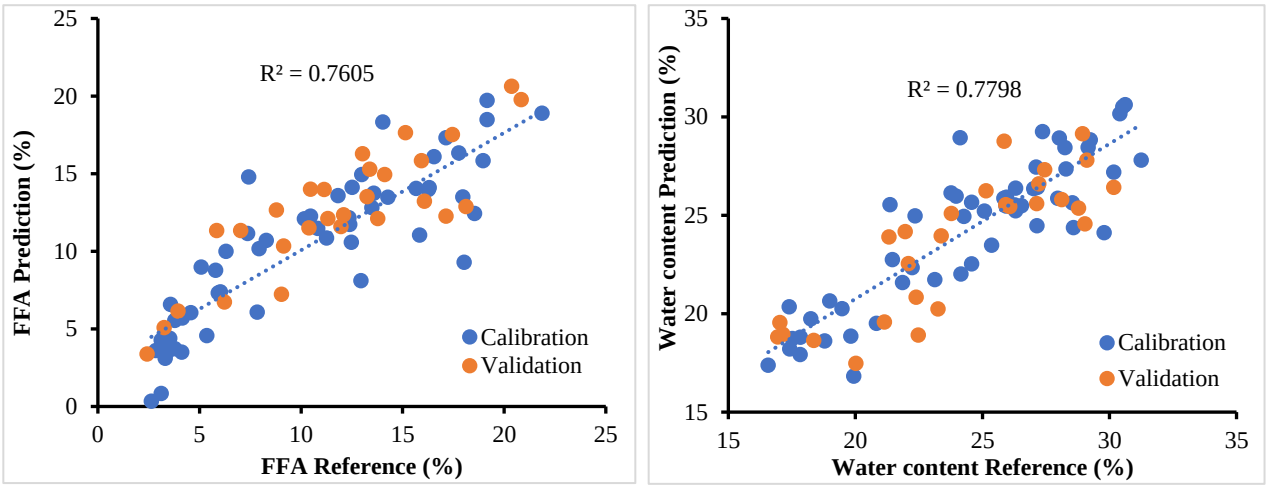

Figure 4 Data distribution of FFA content by PLS method using: (a) SNV pre-treatment, (b) Baseline

3.4.2. Moisture Content

The results of data processing for predicting the value of water content using PLS can be seen in Table 2. The best prediction model is generated using the Baseline pre-treatment method of PLS factor 15. Baseline pre-treatment serves to reduce the impact of transmissions on the resulting impedance spectrum. The coefficient of determination (R^2) value is 0.94. The SEC and SEP values are 3.65% and 3.81% respectively with a CV value of 28.24%, and an RPD value of 1.91This high CV value also indicates a large variation in the data, meaning that the model may be less reliable when applied to palm fruit samples that vary greatly in condition. This underlines that, although the method is promising, the model still requires further development to achieve optimal reliability. The scatter plot of the PLS method moisture content data using SNV pre-treatment factor 15 can be seen in Figure 3b.

Table 2. Data processing results of water content with PLS method

Treatment	Factor	Calibration Set		Validation Set			Consistency
		R^2	SEC (%)	SEP (5%)	CV (%)	RPD	
Original	8	0.72	4.02	4.83	35.73	1.51	83.23%
Normalisasi	12	0.88	2.48	3.32	31.98	1.68	83.51%
Baseline	**15**	**0.94**	**3.65**	**3.81**	**28.24**	**1.91**	**83.24%**
Standard Normal Variate	7	0.73	5.03	6.23	46.12	1.56	80.63%
Multiplicative Scatter Correction	12	0.82	3.16	4.91	36.36	1.58	84.41%

3.5. Calibration and Validation with PCR

3.5.1. Free Fatty Acid Content

Data processing of free fatty acid content with the resulting PCR method can be seen in Table 3. Predictions with the best accuracy in the analysis of free fatty acid content parameters with the PCR method were generated by the Standard Normal Variate (SNV) pre-treatment. In the SNV pre-treatment, the PCR factor of 15 produced R^2, SEC, SEP, and CV values of 0.77, 2.71%, 2.98%, and 25.97%, respectively. The RPD and consistency values are 1.81 and 90.73%. The RPD value is an indication of the suitability of the model for process control that can be improved by increasing the number of measurement samples (Kim *et al*., 2007). The data distribution graph of free fatty acid content of PCR method using SNV pre-treatment factor 15 can be seen in Figure 4a.

Table 3. Data processing results of free fatty acid content by PCR method

Treatment	Factor	Calibration Set		Validation Set			Consistency
		R^2	SEC (%)	SEP (5%)	CV (%)	RPD	
Original	13	0.77	2.61	3.14	27.31	1.72	82.89%
Normalisasi	14	0.82	2.39	2.85	24.78	1.89	83.81%
Baseline	12	0.77	2.61	3.13	27.23	1.72	83.27%
Standard Normal Variate	**15**	**0.77**	**2.71**	**2.98**	**25.97**	**1.81**	**90.73%**
Multiplicative Scatter Correction	14	0.72	2.94	3.16	27.53	1.71	92.82%

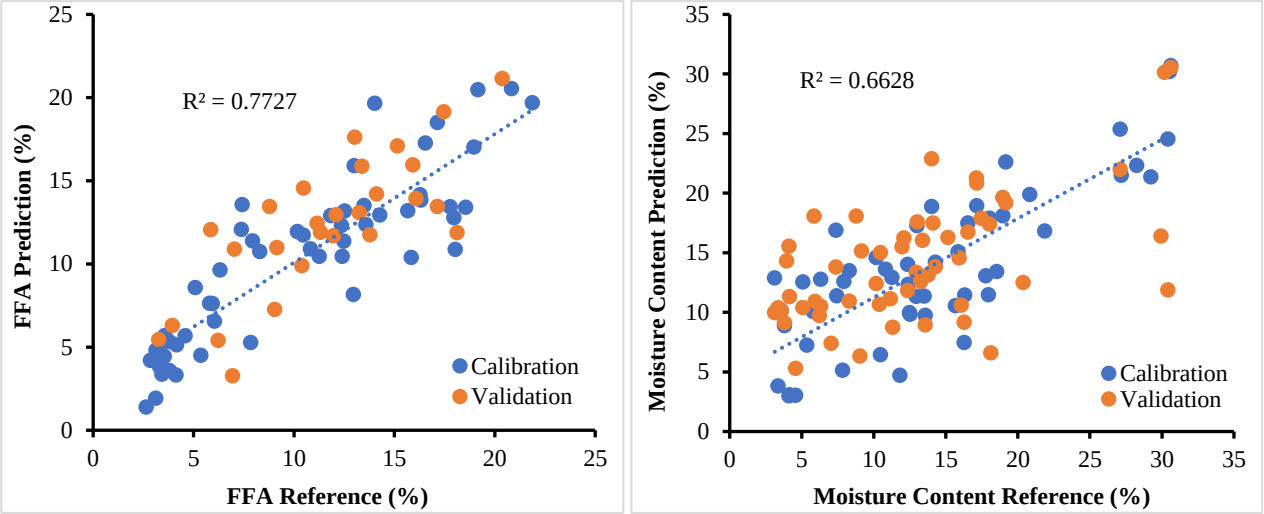

Figure 6. Data distribution of free fatty acid content of PCR method using: (a) SNV pre-treatment, (b) MSC pre-treatment

3.5.2. Moisture Content

The results of the moisture content parameters analyzed by the PCR method are presented in Table 4, while the data distribution graph of the PCR method for moisture content using MSC pre-treatment factor 17 can be seen in Figure 4b. Prediction of moisture content by the PCR method using both the original spectra and pre-treatment resulted in very low accuracy. The prediction with the highest RPD value was obtained from the Multiplicative Scatter Correction (MSC) pre-treatment with PCR factor 15, which was 1.28. The coefficient of determination (R^2) value was relatively low at 0.65. The SEC and SEP values were 4.51% and 5.85%, respectively. This indicates overfitting, as the SEC value is low and the difference between SEC and SEP is too large. Overfitting occurs when the calibration model shows very good performance with calibration data but performs poorly during prediction (Yulia & Suhandy, 2014). Therefore, data processing of the PCR method on moisture content parameters has not been successfully used to predict the water content of oil palm fruit.

Table 4. Data processing results of water content by PCR method

Treatment	Factor	Calibration Set		Validation Set			Consistency
		R^2	SEC (%)	SEP (5%)	CV (%)	RPD	
Original	14	0.42	2.67	3.69	31.77	0.89	72.29%
Normalisasi	9	0.46	6.28	6.87	43.45	0.94	66.84%
Baseline	11	0.57	3.88	5.48	40.54	0.52	70.90%
Standard Normal Variate	15	0.56	5.88	5.94	41.23	0.73	84.24%
Multiplicative Scatter Correction	15	0.65	4.51	5.85	45.41	1.28	76.91%

3.5. Comparative Analysis of Calibration and Validation of PLS and PCR Methods

In this study, the PLS method produced better accuracy than the PCR method. The PLS method for predicting the value of free fatty acid content and water content has met the specified statistical parameters, but the PCR method for water content still does not meet the statistical parameters in the form of RPD value > 1.5, SEC and SEP values close to 0, CV value close to 0, and consistency of 80–110%. The PLS method uses a smaller factor than the PCR method. A high PLS factor value can reduce the ability to make predictions (Jankovská & Šustová, 2003). The use of component factors should also not be too large or small because it can cause overfitting or underfitting.

4. CONCLUSION

This research successfully demonstrated that the combination of Partial Least Squares (PLS) and Electrical Impedance Spectroscopy (EIS) methods can be a non-destructive solution for predicting free fatty acid (FFA) and water content in oil palm fruit during the delayed processing stage. Although the developed model still has room for improvement, the accuracy of this model, with an R^2 value of 0.75 for FFA content and R^2 = 0.94 for water content, shows great potential. The application of this method is very important for the industry because it facilitates quick decision making, which directly increases efficiency and reduces losses. However, this study still has several limitations, such as a limited number of samples and a focus on only two chemical parameters. The RPD value, which is still at a moderate level, also indicates the need for further development. Therefore, further steps are needed to reduce high data variation by increasing the number of samples, improving the measurement system, and refining data processing.

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