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# ANALYTICAL TECHNIQUES FOR THE DETECTION OF PALM OIL ADMIXTURE - A REVIEW

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**ABSTRACT**

*During the crude palm oil (CPO) extraction process, oils are also recovered at certain stages to minimise the oil losses. These recovered oils are known as empty fruit bunch oil (EFBO), steriliser condensate oil (SCO), sludge palm oil (SPO) and palm-pressed fibre oil (PPFO). The quality of recovered oils is inferior to that of freshly pressed CPO, highlighting the need for separate segregation. Effective monitoring of segregation requires the use of screening and detection techniques to identify admixtures in palm oil products. Therefore, this article aims to review the analytical techniques developed, including spectroscopy and chromatography, for detecting palm oil mixed with recovered oil. Despite palm oil admixture detection, the application of analytical technique for adulteration of other fats and oils was also reviewed. The application of Fourier transform-infrared (FTIR) spectroscopy, encompassing the near infrared (NIR) and mid infrared (MIR) regions, when coupled with chemometric techniques such as principal component analysis (PCA) and partial least squares regression (PLSR) analysis, is highlighted as a potential screening technique for detecting palm oil admixtures due to its rapid, practical and the advantage of requiring minimal sample preparation or chemical usage.*

**Keywords:** admixture, blended, palm oil, quality, technical grade palm oils.

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## INTRODUCTION

Oil palm is the foremost crop planted in Malaysia. The trade of palm oil and its products as commodities has significantly contributed to Malaysia's economic growth. In 2023, the crude palm oil (CPO) production was reported at 18.45 million tonnes, while the total export volume of palm oil and oil palm products reached 24.48 million tonnes, generating a revenue of RM94.9 billion (Parveez et al., 2024).

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CPO is extracted from the mesocarp of palm fruits through several processes, including sterilisation, pressing, clarification and purification at the palm oil mill (Abd Majid et al., 2012). The typical oil extraction process in a palm oil mill is illustrated in *Figure 1*. In addition to CPO, some oils are also recovered at various stages within the palm oil mill.

During the sterilisation process, the excess condensate liquor contains a notable amount of recoverable oil, known as steriliser condensate oil (SCO). Besides that, further processing of empty fruit bunch (EFB) through double pressing may also yield some residual oil, known as empty fruit bunch oil (EFBO). Moreover, additional processing of palm mesocarp using a solvent extraction method can recover oil namely, palm-pressed fibre oil (PPFO). At the palm oil mill effluent (POME) discharge, the insoluble residual oil that accumulates on the

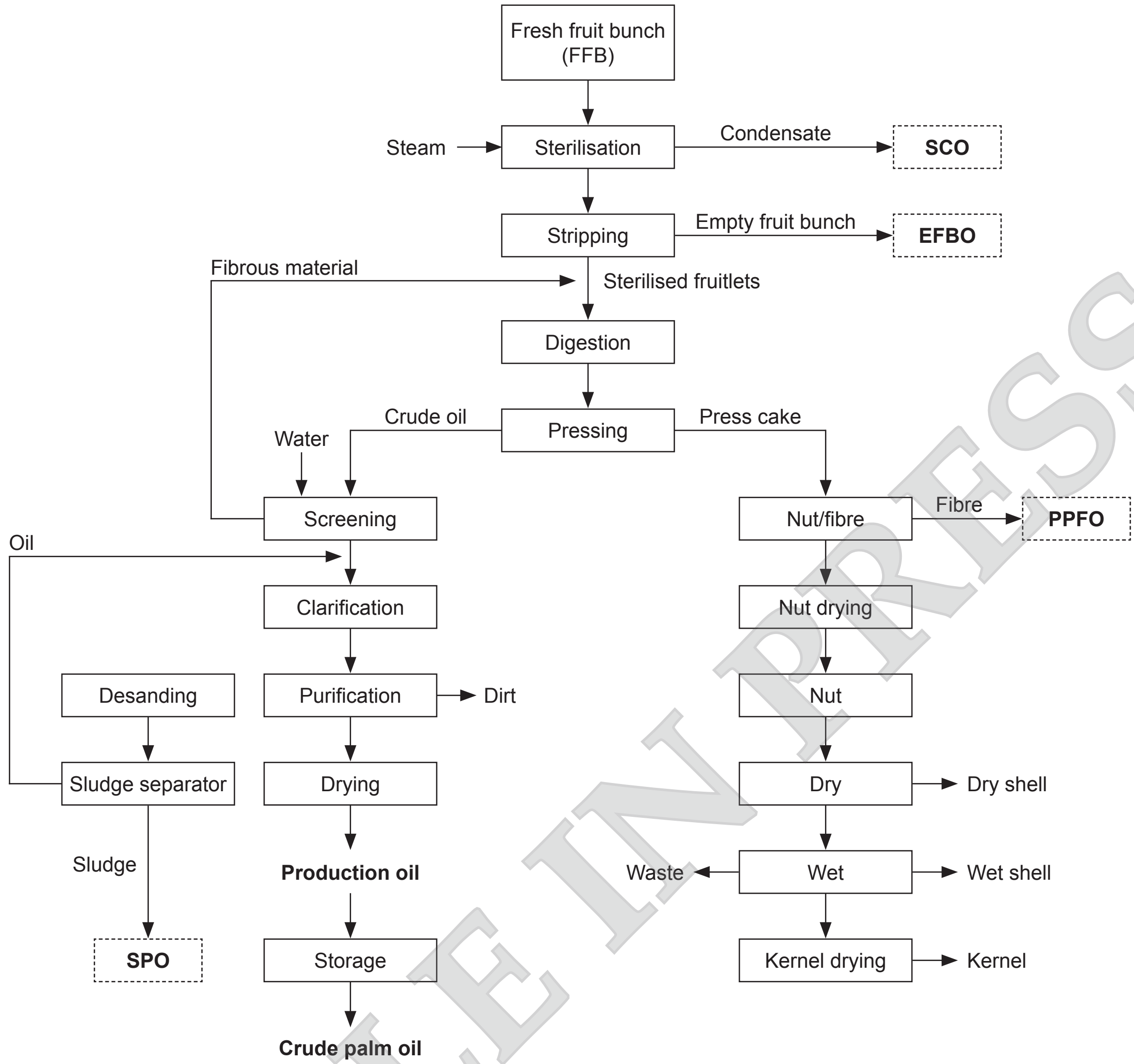


*Figure 1. Common palm oil milling process. The oils recovered are shown in the dashed frame.*

surface of the pond can be separated during the first stage of POME discharge, called sludge palm oil (SPO) (Muanruksa et al., 2019; Wafti et al., 2012). These recovered oils, which are also categorised as technical grade oils, have a lower quality due to the processing equipment, conditions, methods and number of process steps, and exposure to severe oxidising conditions, unwanted compounds and impurities (Chew et al., 2021; Obibuzor et al., 2012). It is more suitable for non-edible applications such as biodiesel production and should be sold as technical grade oils. Blending of these recovered oils into CPO is not recommended as it could affect the final quality of CPO production.

Monitoring and quality assessment are essential tools to ensure that CPO production meets the requirements set by authorised bodies. Therefore, it is essential to establish a suitable technique that is quick and practical for monitoring and detecting the presence of recovered oils in CPO to facilitate reliable assessment. Currently, most study combines analytical techniques such as spectroscopy and chromatography with multivariate analysis, which serves as a predictive tool for identifying patterns and relationships that are not apparent in raw data.

Multivariate analysis, or chemometrics, refers to the application of statistical and mathematical methods to extract meaningful information from complex chemical datasets. It is generally categorised into unsupervised techniques, such as principal component analysis (PCA) and hierarchical cluster analysis (HCA), which are used for data exploration and grouping and supervised techniques, including principal component regression (PCR), partial least squares regression (PLSR), linear discriminant analysis (LDA), support vector machines (SVM), soft independent modeling of class analogy (SIMCA) and k-nearest neighbors (k-NN), which are applied for classification and prediction tasks (Brereton, 2007). By integrating these approaches with modern analytical techniques and large datasets, it helps to enhance pattern recognition and improve the accuracy of chemical quantification and authentication (Rohman et al., 2020; Tan et al., 2022).

Therefore, this article aims to review studies on palm oil blended with recovered oils and the potential analytical techniques for detecting their presence in CPO. A narrative approach was adopted using extensive literature collected from multiple scholarly databases published from the year 1980–2025, including Scopus, Web of Science and Google Scholar. The review is organised into the following sub-categories: (i) Quality characteristics of recovered oils, (ii) study on the effects of blending recovered oils with CPO and (iii) analytical techniques for detecting palm oil admixtures.

## QUALITY CHARACTERISTICS OF RECOVERED OILS

The quality characteristics of recovered oils will be deliberated in the following subtopics.

### Oil Palm Empty Fruit Bunches Oil (EFBO)

Many studies have reported techniques for recovering oil from oil palm empty fruit, however, there are limited studies on the properties and quality characteristics of the recovered oil (Kurnin et al., 2016). In 2014, Gomez et al. (2015) reported that EFBO obtained using a combination of water and steam processes has a high free fatty acid (FFA) content of up to 11.00% and a deterioration of the bleachability index (DOBI) of 1.60. In addition to that, a survey on the quality of EFBO conducted in 2019 reported the FFA range of 6.32%–13.73%, DOBI of 1.18–1.68, total chloride content (TCC) of 4.59 ppm and phosphorus (P) content of 30–45 ppm (Parveez et al., 2019). More recently, Sulaiman et al. (2022) characterised EFBO samples from several mills in Malaysia and found that FFA content of up to 9.43%, and DOBI content of 1.58, which is out from the palm oil specification specified in MS 814:2007. This survey supports the findings reported from the previous studies.

### Steriliser Condensate Oil (SCO)

Sterilisation process has contributed to high condensation rate which resulted of a high oil content in the condensate, which can be recovered at the steriliser pit (Mamat et al., 2017). SCO are normally sold as technical grade oils, while the remaining traces of oil are discharged into the mixing pond. This oil is reported to contain a high iron (Fe) content, which may affect oil stability if blended with CPO (Siew, 2011). In 2019, Parveez et al. reported that the FFA of SCO ranges from 6.72%–30.00%, depending on the type of steriliser used. The high FFA is believed to result from the oxidation and hydrolysis of oil that is retained in the condensate pit for extended periods. Additionally, the DOBI ranges from 1.20–2.10. A recent study also observed that oil extracted from the steriliser had an FFA of 15.56% and a DOBI of 0.13 in the condensate content (Abd Manaf et al., 2022).

### Palm Pressed Fibre Oil (PPFO)

Another type of oil that can be recovered is PPFO, which extracted from palm mesocarp fibre using solvent extraction process. As palm pressed fibre is a mixture of palm mesocarp fibre, kernel shell, crushed kernel and debris, it contains higher level of FFA, P and Cl content compared to CPO (Sylvester & Elijah, 2013). Studies have shown that PPFO contain FFA levels up to 28%, DOBI value of 1.12, P content and TCC of 200 mg $kg^{-1}$, triglycerides ranging from 47%–70% and diacylglycerides from 15%–20% (Mohd Nadzim & Halim, 2019; Sylvester & Elijah, 2013).

### Sludge Palm Oil (SPO)

For the characteristics of SPO, it has been reported to contain FFA levels of up to 86.7%, and DOBI value ranging from 0.02–3.16 (Ibrahim & Kuntom, 2000; Kuntom et al., 1995). It is considered a poor-quality sludge oil resulting from oil leaching at various points during the milling process. SPO can be utilised for non-edible applications such as the production of laundry soap, fatty acids, candles and as a raw material in biodiesel production (Hayyan et al., 2010).

Based on the study of recovered oil characteristics, findings indicate that the oils recovered from the milling process are not suitable to be mixed with fresh CPO as it will affect the quality of the final CPO produced. Moreover, these oils have been reported to contain high levels of chloride, which is known to be a precursor of the process contaminant 3-monochloropropane-1,2-diol ester (3-MCPDE), formed during the refining process. Nevertheless, this recovered oil can be used for non-edible purposes, such as biofuel production.

## STUDY ON THE EFFECTS OF BLENDING RECOVERED OILS WITH CRUDE PALM OIL

To the best of our knowledge, studies on the effect of blending recovered oil with CPO are still inadequate, and many aspects remain to be further explored. A random survey conducted in 2019 discovered an increase in the formation of 3-MCPDE in refined palm oil when CPO was mixed with PPFO at levels ranging from 0.1%–10.0% (Mohd Nadzim & Halim, 2019).

In 2022, Hasliyanti et al. published a study on the implications of CPO quality after blending with PPFO. The results showed that several palm oil quality parameters such as FFA, DOBI, Fe, TCC and copper (Cu), deteriorated with the addition of PPFO into CPO. The properties of CPO blended with PPFO included lower DOBI and iodine value (IV), along with elevated levels of P content, FFA, hexane and trace metals, even at low PPFO ratios. Additionally, the blended oils were found to have high TCC.

A study on the characterisation and quality changes in CPO blended with EFBO, SCO and PPFO at concentrations ranging from 0.5%–10.0% conducted by Sulaiman et al. (2022) showed substantial increases in FFA, Fe content, TCC and P content. A statistical evaluation indicated that the FFA, P, Fe and IV of CPO blended with recovered oils were significantly affected by the increasing dosage.

In this regard, mixing CPO with recovered oils from palm oil mills with the aim to improve the percentage of oil extraction rate (OER) may affect the quality and purity of the final CPO product and reduce the stability of CPO (Siew, 2011). This, in turn, may also affect refining performance as well as the quality attributes of products derived from the oil. Due to these quality effects and food safety concerns, the Malaysian Palm Oil Board (MPOB) Licensing Condition was revised and improved to prohibit the addition of PPFO into CPO (MPOB, 2020).

## ANALYTICAL TECHNIQUES FOR DETECTING PALM OIL ADMIXTURES

Study on palm oil mixed with other palm-based products can be traced back to the 1980s, when detection efforts primarily relied on the measurement of slip melting point (SMP) and IV. These classical physicochemical parameters were employed to assess the compositional changes that occur when palm oil is blended with different palm fractions. However, the application of SMP and IV analyses was found to be more suitable for detecting blends of palm fractions rather than mixtures involving CPO itself, since palm fractions such as palm olein, palm stearin and palm mid-fraction exhibit distinct physicochemical behaviours compared with CPO, particularly in relation to IV and SMP. Despite their usefulness as preliminary indicators, these conventional techniques lacked the sensitivity and specificity required for more complex adulteration studies, which later prompted the development and adoption of advanced spectroscopic and chromatographic methods.

The analytical techniques established for the detection of palm oil mixed with its products admixture are summarised as in *Table 1*. Based on the literature findings, many studies focused on used cooking oil (UCO) or recycled cooking oil (RCO) as the adulterant mixed with palm oil. With respect to recovered oils, SPO has received the greatest research attention as compared to EFBO, SCO and PPFO.

In order to provide a broader perspective on analytical techniques, methods that have been developed for the detection of other adulterants including animal fats, dyes and lard are also reviewed and summarised in *Table 2*. This comparative review not only highlights the applicability of these techniques beyond palm oil adulteration but also offers insights into their potential adaptability for detecting palm oil admixtures.

The most widely explored analytical technique for detecting palm oil mixed with other palm products is Fourier transform-infrared (FTIR) spectroscopy, applied in both the NIR and MIR regions. This is followed by chromatographic techniques, such as triacylglycerols (TAG) and fatty acid composition (FAC) analysis, as well as dielectric property measurements. For palm oil adulteration with other products, the most frequently studied is lard, followed by Sudan dyes, other animal fats, leaf extracts and food colourants. The presence of lard in palm oil has drawn significant attention because of its implications for halal compliance, given that pork-derived products are strictly prohibited in Islamic dietary laws. For these products, in addition to FTIR spectroscopy, TAG and FAC analyses, other analytical techniques have also been developed, including Raman spectroscopy, UV-Visible spectroscopy, electronic nose (e-nose) systems and differential scanning calorimetry (DSC).

FTIR spectroscopy has been widely used due to its cost-effectiveness, rapid technique, minimal sample preparation, high accuracy and sensitivity, good reproducibility and suitability as a fingerprint analytical tool (Baeten et al., 2001; Jamwal et al., 2021; Qu et al., 2015). This advantage has rendered it the most significant technique for fingerprinting purposes. It is an ideal method for characterising the chemical structure of analyte compounds and the evaluation of functional groups including chemical compounds present in food samples (Mashodi et al., 2020; Tan et al., 2022). It also provides qualitative data on oils and fats samples by identifying organic groups through the vibrations of molecular bonds, which occur due to specific functional groups in the IR spectrum at pre-determined wavenumbers.

In addition, the chemical composition of palm oil has been extensively investigated, with FAC determined using gas chromatography coupled

**TABLE 1. SUMMARY OF DETECTION TECHNIQUES FOR PALM OIL AND ITS PRODUCT ADMIXTURES**

| Blending product | Technique | Findings | Chemometrics analysis | References |
|---|---|---|---|---|
| Palm oil blended with palm stearin | SMP, IV, TAG, FAC | In the study, palm oil blended with palm stearin at 2%–40% was prepared and analysed for SMP, IV, TAG and FAC. Results showed that the hard stearins with IV 21 samples were more easily detectable when mixed with palm oils of IV 55, which could be detected in amounts as low as 4%. | Not available | Tan et al. (1983) |
| Crude palm kernel oil (CPKO) mixed with refined palm oil and refined palm olein | SMP, IV, TAG, FAC | In the study, CPKO mixed with refined palm oil and refined palm olein samples at 1%–20% were prepared and analysed for SMP, IV, FAC and TAG. Results observed that the relationship between triglycerides carbon number C48 to C52, C36 and C38 was transformed to give patterns expected of authentic palm kernel oil samples. | Not available | Siew (1989) |
| CPKO blended with CPO and other palm products and by-products | NIR and solid fat content (SFC) by pulse-nuclear resonance magnetic | NIR can be used for detecting certain adulterants such as scavenger, ester bottom, soap stock and alcohol bottom at below 10% in CPKO. For CPKO blended with palm products such as CPO, RBDPO, palm olein and palm stearin, the detection using NIR is feasible for blending levels of more than 10%. However, for blending levels of less than 10%, SFC was able to detect. | Not available | Yusof and Chong (2008) |
| CPO mixed with SPO and UCO | FAC and TAG | The UCO was prepared by cooking French fries and chicken nuggets. The percentage of admixture added to palm oil in the study ranged from 1%–20%. PCA allowed the segregation between CPO and adulterant (SPO and UCO) and gave variable loadings for each separated group. The adulterant level as low as 5% and 2% (v/v) was able to be detected by PCA and dendrogram correspondingly. | PCA; dendrogram | Inthiram et al. (2015) |
| CPO mixed with SPO | Dielectric properties | Dielectric properties of CPO were measured at different temperatures and SPO was mixed at 0.6%–10.0% levels using a liquid dielectric test fixture that was connected to an impedance analyser with frequencies ranging from 3–30 MHz. PCR and PLS analyses were used for model development to predict sludge contamination. The results showed that there was a significant difference in dielectric constant as the temperature increased from 28°C–55°C ($p<0.0001$). The PCR and partial least squares (PLS) calibration models showed good prediction ability of sludge contamination at different temperature levels. | PCR; PLS | Hamdan et al. (2015) |
| CPO mixed with SPO and PPFO | Gas chromatography-ion mobility spectrometry (GC-IMS) | The study observed that the application of GC-IMS technique is suitable for initial screening of CPO mixed with residual oils, SPO and PPFO at 1%–10% (w/w). Detection of a reliable PFO fingerprint in spiked dispatch tank samples was not possible. However, a significant SPO fingerprint was detected in all spiked dispatch tank samples and spiked lab-pressed CPO (down to 1% (w/w) SPO). The SPO fingerprint was characterised by 21 VOCs and spanned four spectral regions. | Not available | Othman et al. (2019) |

**TABLE 1. SUMMARY OF DETECTION TECHNIQUES FOR PALM OIL AND ITS PRODUCT ADMIXTURES (continued)**

| Blending product | Technique | Findings | Chemometrics analysis | References |
|---|---|---|---|---|
| Palm olein blended with RCO | FTIR spectroscopy and fatty acids compositions | The RCO were prepared by frying fried banana and chicken nuggets, followed by washing, degumming, bleaching and deodorisation processes. For PLS calibration model, the lowest FTIR predicted adulteration level was 4.72%, while the lowest actual adulteration level was 1%. DA classification model that classified the FPO and AO into two distinct groups, where the percentage of variation is 42.50%. This indicated that this DA model is able to 100.00% accurately differentiate the oil samples according to its group, even though the adulterated oils with the adulteration level as low as 1.00%. Several fatty acids which were not found in palm olein, such as, C8:0, C10:0, C11:0, trans- C18:1 and C20:5, were detected in RCO in trace amounts (<0.1%). The presence of C8:0 (0.03 ± 0.02%), C10:0 (0.02 ± 0.01%) and C20:5 (0.05 ± 0.03%) in RCO was due to the migration of fats from the fried items into the frying oil during the frying process. | DA; PLS | Lim et al. (2018) |
| CPO blended with UCO | MIR and FT-NIR | The UCO produced (cooked with lard, fish, beef and lamb) was mixed with fresh and authentic CPO at different proportions of 5, 10, 20 and 30 (weight/weight) (m/m %). The findings observed that the FT-NIR and FTIR are suitable for authenticity screening with 96.7% correct classification on FTIR and 83.3% correct classification on FT-NIR. For quality screening, the classification effectiveness is only 42.4% and 36.0% for both FTIR and FTNIR techniques. | DA | Ng et al. (2019) |
| Palm oil adulterated with RCO | Handheld NIR spectroscopy | Palm oil and palm oil mixed with RCO produced by deep-fried with chicken nuggets and French fries at different concentrations from 1%–50% were analysed using handheld NIR at wavelength 900–1,700 nm. A band at 1,450 nm that corresponding to –OH first overtone stretching vibration shown to be wider and intense in recycled cooking oil as compared to pure palm oil, indicating a greater intensity of band absorbance. The palm oil mixed with RCO at above 15% concentration demonstrated classification precision of 100%. | PCA | Irfan et al. (2020) |

**TABLE 2. DETECTION OF PALM OIL BLENDED WITH OTHER OILS AND PRODUCTS**

| Product | Technique | Findings | Chemometrics | References |
|---|---|---|---|---|
| RBD palm oil blended with lard | DSC | In the study, RBD palm oil was blended with lard in proportions ranging from 0.2%–20.0%. The DSC cooling profiles of adulterated RBD palm oil samples showed an adulteration peak corresponding to lard/randomised lard in the low-temperature region. This peak was confirmed as an indicator of the presence of lard in RBD palm oil. Using this method, a detection limit of 1% lard/randomised lard was reached (*P*<0.0001). | Not available | Marikkar (2001) |

**TABLE 2. DETECTION OF PALM OIL BLENDED WITH OTHER OILS AND PRODUCTS (continued)**

| Product | Technique | Findings | Chemometrics | References |
|---|---|---|---|---|
| RBD palm olein blended with lipase-catalysed interesterified lard | DSC, TAG and FAC | The presence of lipase-catalysed interesterified lard in RBD palm olein was examined using FAC, TAG and DSC. Among the methods employed, DSC was most effective at detecting lard using its thermal characteristics, even at 1% levels. DSC was more sensitive for both quantitative and qualitative determination of lard in palm oil. | Not available | Marikkar (2002) |
| RBD palm olein blended with lard | e-nose | The mixtures of RBD palm olein blended with lard at levels ranging from 1%–20% (w/w) were measured using distinct peaks in the zNoseTM chromatogram. The findings of the study observed that the use of zNoseTM for detecting lard in RBD palm olein offered a more sensitive method that does not require sample pre-treatment or chemical reagents, and also offers good accuracy and speed for quality control purposes. | Not available | Che Man et al. (2005) |
| Palm oil blended with lard | FTIR spectroscopy | FTIR spectroscopy in combination with multivariate calibration of PLS can be successfully used for quantification of lard in French fries down to 0.5%. DA can make a classification between palm oil and palm oil adulterated with lard extracted from French fries samples. | PLS; DA | Che Man et al. (2014) |
| CPO blended with lard | FTIR spectroscopy | The developed analytical method identified the wave number FTIR which has characteristics to detect the presence of lard in CPO at a ratio 25%–75%. The PLS model built gives a good result of the correlation between actual value and predicted value with an $R^2$ value of 0.998. | PLS | Ahda and Safitri (2016) |
| Palm oil blended with lard | Micro NIR | Palm oil blended with lard at concentrations from 0.5%–50.0% was tested in this study. The pure and adulterated sample can be discriminate and quantify the percentage of adulteration with $R^2$ approximately 99.0% accurate. | SIMCA; PLSR | Basri et al. (2017) |
| Palm olein blended with lard | FT-NIR, MicroNIR and LED-NIR | Comparison of FT-NIR, micro-NIR and LED-NIR techniques to detect the lard blended into palm olein at concentrations of 0.5%–50.0%. The NIR spectra data were combined with PLS and LDA. LDA result showed that LED-NIR outperform FT-NIR and MicroNIR with a sensitivity of 1.00 and specificity of 0.9333. | PLS; LDA | Basri et al. (2018) |
| Palm olein blended with lard | FTIR spectrophotometer | In this study, palm olein blended with lard at concentrations of 20% and 50% was used. Based on Fisher Weights, five peaks at 3,006, 2,852, 1,117, 1,236 and 1,159 $cm^{-1}$ were identified as variables with the most significant discriminatory ability. These peaks were reported to decrease in intensity with increasing concentration of lard. The PLSR model demonstrates better accuracy as compared to the SLR and multiple linear regression (MLR) models. | SLR; MLR; PLSR | Sim et al. (2018) |

**TABLE 2. DETECTION OF PALM OIL BLENDED WITH OTHER OILS AND PRODUCTS (continued)**

| Product | Technique | Findings | Chemometrics | References |
|---|---|---|---|---|
| Palm oil blended with lard | FTIR spectroscopy | In this study, palm oil was blended with lard at a concentration of 25.00%–75.00%. The result of LDA shows the first discriminant function which is obtained with a variance value of 99.30% and the second discriminant function with a variance value of 0.07%. PLS regression shows the results seen from the validation error value (RMSECV) of 3.85 and the calibration error value (RMSE) of 0.64. | LDA; PLS | Tazi (2023) |
| Refined palm oil blended with lard | FAC | Refined palm oil blended with lard at a concentration of 1%–10% was tested in this study. PCA has shown that three significant fatty acid; trans linoleic acid (C18:2n6t), cis oleic acid (C18:1n9c) and palmitic acid (C16:0) can be observed in all the loading plots. The addition of 10% lard contributes significantly to other samples in the scores plot. | PCA | Salleh and Hassan (2015) |
| RBD palm oil blended with lard | Gas chromatography mass spectrometry headspace (GC-MS-HS) | This study was to analyse the pattern of volatile compounds for different percentages of lard (0, 15, 30) in RBD palm oil when heated at three different temperatures (120°C, 180°C, 240ºC) for 1, 2 and 3 hr. GC-MS-HS was used to analyse the volatile compounds released in the sample. The characteristics of volatile compounds were clustered according to the heating temperature. | PCA | Sulaiman et al. (2019) |
| Palm oil mixed with chicken fat | FT-NIR spectroscopy | The chicken fat was blended with palm oil at concentration ranges of 28.50%–48.28%. The LDA model-built result classification of the palm oil samples blended with 31.80% adulteration and above was feasible. | LDA | Khir et al. (2014) |
| Palm oil mixed with beef tallow | NIR spectroscopy | The palm oil is mixed with beef tallow at concentrations from 0.5%–50.0%. The addition of beef tallow as low as 0.5% can be predicted using a PLS regression model. | LDA; PLS | Khir et al. (2018) |
| Palm oil adulterated with Sudan dyes | Portable Visum NIR spectroscopy | The palm oil is adulterated with Sudan dyes at percentages 0.0009%–0.5000%. The PCA plots showed that there were clear cluster trends observed, revealing pure and adulterated palm oil samples. For LDA and SVM, results show that both models performed optimally above 91% identification rate at PCs 37 for the identification of adulterated palm oil with Sudan dye. | PCA, LDA, Support vector machine | Teye et al. (2019) |
| Palm oil adulterated with Sudan dyes | Refractometer and UV/VIS/ NIR spectrophotometer | Palm oil is adulterated with Sudan dyes at percentage between 5%–25%. NIR spectrophotometer over the wavelength range 400–2,500 nm combined with excess RI. The technique developed allows a fast screening of a large set of samples. | PCA | Andoh et al. (2020) |
| Palm oil adulterated with Sudan IV dye | Shortwave handheld NIR spectroscopy | Palm oil is adulterated with Sudan IV dye at a percentage of 0.100%–0.002% (w/w). The developed multiplicative scatter correction plus KNN technique was found to accurately classify, where, R = 95.48% and 97.00% in the calibration set and prediction set respectively. | PCA; PCR; PLSR; K-NN classification | MacArthur et al. (2020) |

**TABLE 2. DETECTION OF PALM OIL BLENDED WITH OTHER OILS AND PRODUCTS (continued)**

| Product | Technique | Findings | Chemometrics | References |
|---|---|---|---|---|
| CPO mixed with Sudan II and IV dyes | Surface-enhanced Raman spectroscopy (SERS) Hollow Au@Ag Nanoflower sensor | In the study, CPO was mixed with Sudan II and IV dyes ranging from 0.005–4.000 ppm. Competitive Adaptive Reweighted Sampling (CARS-PLS), Genetic algorithm-PLS (GA-PLS), and bootstrapping soft shrinkage-PLS (BOSS-PLS) were used to develop quantitative models for Sudan dyes prediction. The CARS-PLS model performed best for Sudan II and IV, with $R^2$ values of 0.9921 and 0.9846, respectively and real sample recovery rates of 98.79%–104.49% and 94.37%–109.59%. | PLS | Adade et al. (2022) |
| CPO mixed with Sudan dyes (I - IV) | SERS-based Au@Ag substrate sensor | In the study, CPO mixed with Sudan dyes (I-IV) at concentrations from 0.001–4.000 ppm was prepared. The genetic algorithm partial least square (GA-PLS) model outperformed the partial least square (PLS) and the ant colony optimisation-PLS (ACO-PLS) models with $R^2$ values of 0.9844, 0.9865, 0.9884 and 0.9888 0.9846, respectively. | PLS | Adade et al. (2024) |
| Palm oil mixed with leaf extract and food colour | UV-Visible spectrometry | The sample mixtures covered concentration ranges of 0.133–1.333% w/v adulterant. LDA models were able to classify different concentrations of sorghum leaf dye and food colour in crude palm oil with good accuracy. The results suggest a potential for rapid detection of concentrations as low as 0.2 g/mL of food colour in CPO and colour extract from a sorghum leaf size 10 cm by 1 cm. | LDA; PLSR | Zaukuu et al. (2024) |

with a flame ionisation detector (GC-FID), and TAG analysed by high-performance liquid chromatography (HPLC). However, these techniques require sample preparation, which increases the time needed for analysis. Triglycerides in palm oil degrade primarily during heating through hydrolysis and oxidation of unsaturated fatty acids, while the relatively high saturated fat content (palmitic acid) contributes to its greater stability compared with oils richer in polyunsaturated fats (Khor et al., 2019; Teh et al., 2020).

Raman spectroscopy measures inelastic scattering of laser light due to polarisability changes in molecular vibrations, which is based on the Raman effect (Shipp et al., 2017). The technique provides a unique and detailed molecular fingerprinting through vibrational information, allowing the differentiation of oils based on subtle compositional variations, chemical structure, functional groups and degree of unsaturation in edible oils (Ghazali et al., 2024). Raman also likes FTIR, a non-destructive technique which is quick and requires minimal sample preparation. However, it is more sensitive to non-polar bonds such as C=C and C–C as compared to FTIR which is very sensitive to functional groups like C=O, O–H, and C–H.

UV-Visible spectroscopy is an electronic spectroscopic technique that measures the absorption of ultraviolet (200-400 nm) and visible light (400-700 nm) by molecules. This spectroscopy is particularly useful for detecting chromophoric compounds such as carotenoids and pigments, and also oxidation products, which serve as indicators of oil quality (Jolayemi et al., 2018). While UV-Visible cannot provide as much structural detail as techniques like FTIR, Raman, or chromatography, its speed, low cost and ability to track oil quality changes make it an effective first-line screening tool in both laboratory and industrial settings.

The e-nose is an analytical device designed to mimic the human olfactory system in detecting and discriminating odours. The technique is simple, rapid and highly sensitive to volatile compounds which can then detect the trace levels of oxidation products. It is typically composed of a sensor array, a pattern recognition system and a signal acquisition system. When edible oils degrade through oxidation, hydrolysis or heating, they release distinct VOCs such as aldehydes, ketones, alcohols and short-chain fatty acids. The e-nose captures these VOC profiles and produces a unique odour fingerprint and rancidity that can be linked to oil type, freshness or adulteration status (Gan et al., 2005).

DSC, on the other hand, characterises thermal transitions such as melting and crystallisation, offering valuable information on the physical and structural properties of oils and their blends and is influenced by physicochemical properties such as FAC, TAG and chemical structure (Zulkifli et al, 2024). Collectively, these complementary methods enhance the robustness, accuracy and reliability of analytical approaches for palm oil adulteration detection.

In addition to instrumental data, the combination with chemometrics methods such as simple linear regression (SLR), PCA, PCR, DA, LDA, PLS and partial least square regression (PLSR) has resulted in a meaningful observation for predicting, differentiating and clustering samples based on their properties. Chemometric techniques play a crucial role in the pre-treatment of spectral data, as they help minimise noise, correct baseline shifts and address overlapping signals, thereby enhancing the accuracy and reliability of subsequent classification and prediction (Rinnan et al., 2009; Yan, 2025).

### Gap Analysis

This review indicates that most studies on palm oil admixture have primarily focused on blends involving SPO followed by PPFO. However, there is a clear lack of study examining the blending of EFBO and SCO with CPO. This gap highlights the need for further investigation into these recovered oils, as their incorporation into CPO may pose unique challenges in terms of detection, quality assessment and authenticity verification. Addressing this gap would provide a more comprehensive understanding of the potential adulteration pathways and strengthen the development of reliable analytical techniques for palm oil authentication.

## CONCLUSION

This reveals that investigations into the palm oil mixed with recovered oils are still relatively limited. Among the various analytical tools explored, FTIR spectroscopy emerged as the most frequently applied technique. Its advantages, particularly rapid measurement, non-destructive analysis and minimal sample preparation, make it a promising screening method for detecting palm oil admixtures. The integration of FTIR with chemometric approaches such as PCA, PLS and regression models further enhances its reliability and effectiveness in classification and prediction. In addition to FTIR, other spectroscopic and chromatographic methods, including Raman spectroscopy, UV-Visible, TAG and FAC profiling, have also demonstrated potential for identifying adulteration with recovered oils. These complementary techniques may provide deeper insights into compositional changes and improve detection accuracy when used alongside the chemometric modelling. Despite these advances, there remains a need for broader study to evaluate and validate alternative analytical strategies that are both rapid and practical for industrial application. Developing such methods will be essential for establishing effective and accessible screening systems to ensure the authenticity and quality of palm oil and its products.

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