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Factors affecting crude palm oil quality across the supply chain and implications for downstream industries in North Sumatra and Riau

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Abstract

Crude Palm Oil (CPO) quality, which is vital for downstream industries, is affected by multiple supply chain factors. This study investigated these factors and industrial needs in North Sumatra and Riau, Indonesia's key provinces for CPO production. Methods included supply chain investigations Fresh Fruit Bunch (FFB) production, Palm Oil Mill (PMO) processing, and CPO transport/storage, a refinery case study, and a Focus Group Discussion (FGD) with downstream industries. FFB handling practices, including loose fruit diversions, impacted mill intake quality. PMO processing significantly altered Free Fatty Acid (FFA), Moisture and Impurities (M&I), and Deterioration of Bleachability Index (DOBI). Substantial DOBI degradation and FFA increases occurred during CPO transportation and storage at the refinery due to oxidation and hydrolysis. Downstream, the refining and oleochemical sectors require high CPO quality (e.g., high DOBI and low FFA), whereas the biodiesel sector is more flexible. PMO operational alignment with advanced quality metrics like DOBI was limited. This study concludes that CPO quality is vulnerable throughout its supply chain, particularly post-milling. The findings necessitate an integrated approach that includes improved FFB handling, optimized PMO processing, and enhanced logistics to minimize degradation and align production quality with the specific demands of each downstream sector. Such an approach is crucial for improving the overall efficiency and competitiveness of the Indonesian palm oil industry.

[Keywords: FFB quality, industrial requirements, palm oil processing, storage effects, transportation]

Introduction

The palm oil industry is a strategic sector for the Indonesian economy, vital for foreign exchange, income, employment, national energy development, and equitable economic distribution. Its substantial economic impact is well-documented, with the agricultural sector, particularly palm oil, through production growth and area expansion, significantly contributing to Indonesia's Gross Domestic Product (GDP), creating millions of jobs in the plantation sub-sector, boosting trade, and improving community living standards (Pusat Data dan Sistem Informasi Pertanian Kementerian Pertanian, 2022; Rahmah et al., 2022). Over the past decade, this industry has undergone rapid quantitative expansion in both plantation area and CPO production volume (Khatiwada et al., 2021; Mehraban et al., 2021).

Nevertheless, the quality aspects of CPO, a primary raw material for the continually developing downstream industries, have often not received the commensurate attention they deserve. CPO quality, however, is a critical determinant of the efficiency of further processing and the quality of the final products (Sari et al., 2021; Sembiring & Ramzani, 2020). Issues such as relatively stagnant land productivity and variations in FFB quality from various plantation management types, particularly smallholder plantations, also contribute to the diversity of CPO quality (Imaroh & Efendi, 2020; Mohammad et al., 2021; Sampaio et al., 2017).

CPO quality is not solely determined at the point of extraction in PMO but is the cumulative result of various factors along its entire supply chain (Witjaksono et al., 2023). This ranges from cultivation practices and FFB harvest management at the plantation level, diversity in machinery design, equipment, and processes within PMO, to handling practices during CPO transportation and storage before delivery to down-

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stream industries (Arif et al., 2024; Azmi et al., 2024). Each of these stages has the potential to cause changes or deterioration in CPO quality, for instance, through hydrolysis, which increases FFA content, or oxidation, which affects the oil's stability and other characteristics, such as the DOBI. Understanding this web of influences, where the outcome of one stage becomes the input for the next, is challenging; thus, the precise and holistic impact on CPO quality across the entire supply chain is often not fully understood (Sarjono et al., 2022; Hudori et al., 2023).

Comprehensive studies on the influence of various factors in each supply chain segment on the resulting CPO quality remain minimally reported within the Indonesian industrial context, particularly those taking a holistic approach. Such endeavors would ideally need to comprehensively integrate quality analysis throughout the entire value chain—from the influence of plantation practices and FFB handling, through the intricacies of PMO processing, to the impacts of post-mill handling and logistics. Crucially, these integrated analyses must then be able to bridge the gap by explicitly linking these upstream and midstream quality variations to the often stringent and differentiated quality demands of diverse downstream sectors (oleofood, oleochemical, and bioenergy). This type of comprehensive, end-to-end mapping of quality determinants against specific industrial end-use requirements is especially vital, yet less explored, particularly in pivotal production centers like North Sumatra and Riau (Hidayat et al., 2020; Choiruzzad et al., 2021; Rosyadi et al., 2021; Sihombing & Purwoko, 2025).

Concurrently, the diversification of palm oil-based downstream products in Indonesia continues to expand rapidly, encompassing oleofood groups, oleochemicals, and bioenergy. Each of these downstream industry groups has different and increasingly specific requirements for CPO raw material or its refined products. The oleochemical industry also requires CPO with specific characteristics for process efficiency and final product quality. In contrast, the biodiesel industry may have a greater tolerance for certain quality parameters but still requires a consistent supply of CPO. This growing variety of requirements, ranging from the demand for high oxidative stability in the food sector to specific purity criteria for the oleochemical industry, logically demands more than just a general understanding. An urgent industrial need, therefore, arises to move beyond a generic approach to CPO production and handling. Such understanding is crucial for aligning variable upstream outputs with the precise quality demands of each distinct downstream sector.

A lack of available CPO quality mapping and an understanding of these specific needs can lead to CPO misallocation, where high-quality CPO may not be optimally utilised, or vice versa. Given the complexity of factors affecting CPO quality throughout the supply chain, the diverse needs of downstream industries, and the vital role of North Sumatra and Riau Provinces as national CPO production centres (contributing nearly a third of Indonesia's total production), in-depth research in these two regions is crucial.

This study, therefore, aims to comprehensively examine the factors that cause variability and potential quality deterioration of CPO in each primary supply chain segment, from upstream plantations through PMO processing, to handling during CPO transport and storage in North Sumatra and Riau. Furthermore, this research also seeks to identify the relevant CPO raw material or derivative quality specification requirements for each major downstream industry group (oleofood, oleochemical, and oleoenergy). It is anticipated that the findings of this research will provide strategic input for stakeholders in efforts to enhance efficiency, optimise CPO utilisation, and improve the overall competitiveness of the Indonesian palm oil industry.

Materials & Methods

This research employed a multi-faceted approach, encompassing surveys across various segments of the palm oil supply chain, detailed laboratory analyses of CPO samples, and consultations with industry stakeholders, including a FGD. To identify the CPO quality specifications required by different downstream sectors in North Sumatra and Riau provinces, the study investigated three main industry groups: oleofood (refineries), oleochemicals, and bioenergy/biodiesel. Data was collected through a combination of literature reviews, interviews, questionnaires, and direct site visits to key large-scale producers representing these sectors. The information was then validated through a FGD with academic experts and industry practitioners from all three sectors.

Assessment of CPO quality requirements of downstream industries

To identify the CPO quality specifications required by different downstream sectors, data on downstream industries (oleofood, bioenergy/ biodiesel, and basic oleochemicals), including their locations and company profiles, were initially collated through literature reviews and discussions with regulatory bodies such as the Ministry of Industry, provincial industry agencies, the Ministry of Energy and Mineral Resources, and relevant producer associations. Following the initial data collation, specific quality requirements for CPO and its derivatives as industrial raw materials were identified through questionnaires and direct interviews with a limited number of key producers, conducted from July 2024 to January 2025. These findings were later clarified and validated in a FGD involving experts from the three main downstream sectors. Key large-scale producers representing the oleofood (refineries), oleochemical, and biodiesel sectors were also visited for in-depth data collection and site observations. The collated information was further clarified and validated through a FGD involving academic experts from Universitas Sumatera Utara, Universitas Nommensen and IPB University and industry practitioners from PT Anugerah Agro Sawit Perkasa, PT Industri Nabati Lestari (INL), PT SOCIMAS, Asosiasi Produser Biofuel Indonesia (APROBI), GAPKI, PT SOCIMAS, representing the oleofood, oleochemical, and biodiesel sectors. Parameters such as the DOBI content were specifically explored as potentially important quality indicators.

Survey of CPO quality variation at the FFB production segment

The investigation into CPO quality variations originating from FFB production focused on assessing FFB quality based on the Ripeness Sortation Value (RSV), a widely used industry metric. Plantation businesses were classified into three categories: large private and state-owned plantation companies, organised smallholders (plasma schemes, cooperatives, partnered independent smallholders), and independent smallholders. Data on plantation areas and production, categorized by business type, were obtained from official statistics and relevant provincial/district plantation agencies, in coordination with producer associations, for each district in North Sumatra and Riau. Plantations were selected using purposive sampling, considering the traceability of FFB quality to specific PMO and variations in land conditions (mineral versus peat/wetlands). From each selected PMO, FFB samples were collected, representing different supply sources (e.g., own plantation, organized third-party smallholders, and independent third-party smallholders, collected through intermediaries). Two FFB samples from each source were processed through the mill's sterilisation station, and the CPO was then manually extracted using a specialised mini-hydraulic press designed by the Indonesian Oil Palm Research Institute (IOPRI). The extracted CPO was dried in an oven before being transported for laboratory analysis of key quality parameters.

Survey of CPO quality variation during PMO processing

To assess CPO quality variations occurring during PMO processing, PMO in North Sumatra and Riau were initially identified through consultations with provincial plantation agencies and industry associations. PMO were broadly classified based on their FFB sources (e.g., mills with own nucleus plantations, mills sourcing from partnered smallholders, and independent mills relying entirely on unorganised independent smallholders). A detailed questionnaire was administered to all registered PMO in both provinces to collect data on their CPO production quality (SNI 2901:2021 parameters and DOBI) over the preceding two years, along with information on FFB sources and average FFB quality. Additionally, these PMO were requested to send two CPO production samples to IOPRI for comprehensive quality analysis. Approximately 5% of the PMO population in both provinces were subsequently visited for on-site questionnaire clarification and direct CPO sampling at various critical processing points within the mill (e.g., post-sterilisation, crude oil from screw press, clarified oil, vacuum dryer output, storage tank) to track quality changes during processing.

Survey of CPO quality changes during post-processing handling and transportation

Changes and variations in CPO characteristics due to post-processing handling in storage tanks and different distribution/transportation modes were investigated by tracing CPO quality from PMO storage tanks, through various transportation methods, to shore tanks at ports or bulk storage tanks at refineries. For selected PMO, CPO samples were taken from their bulk storage tanks (representing both fresh daily production and CPO dispatched for delivery). The CPO storage and dispatch operations were then followed to the destination (shore tank or downstream processing plant, such as a refinery), where further CPO samples were taken before entry into the destination storage tanks. Samples were also taken from port/plant storage tanks that were soon to be distributed or used in processing. All collected CPO samples from these stages were analysed at the IOPRI laboratory. A specific case study was conducted at PT INL to examine the changes in CPO quality during transportation to and storage at a refinery.

Laboratory analysis of CPO samples

Unless specified otherwise, CPO samples collected across all survey segments were analysed at the accredited laboratory of IOPRI for a comprehensive suite of quality parameters. Key parameters included: moisture and impurity content (AOCS Ca 2c-25 2003), FFA content (AOCS Ca 5a-40 2003), and DOBI value (PORIM Method P2.9, 1995). Other parameters relevant to specific analyses, such as Peroxide Value (PV), Anisidine Value (AV), and carotenoid content, were also determined using standard analytical methods.

Data analysis

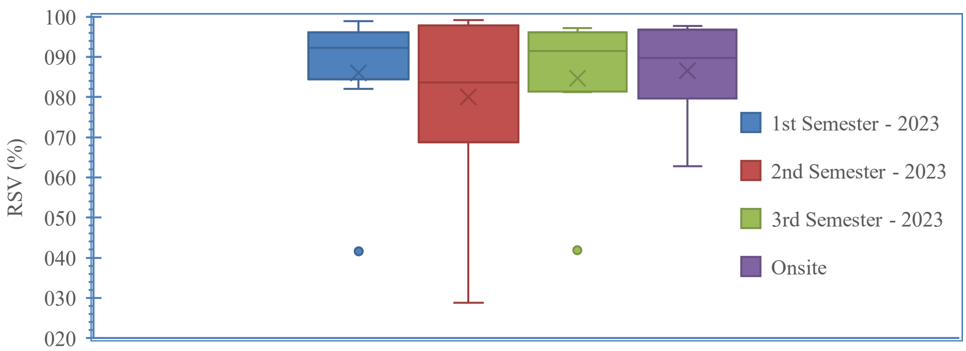
Data on CPO quality specifications from downstream industries were analysed descriptively. For quantitative data on CPO quality parameters from the various survey segments, descriptive statistics were employed. Correlation analyses and appropriate statistical tests (e.g., t-tests, ANOVA, as applicable) were used to identify relationships between CPO quality variations and the investigated factors within each segment of the supply chain (FFB production, PMO processing, and handling/transportation).

Results and Discussion

Factors influencing CPO quality at the FFB production stage

The quality of FFB entering PMO is a primary determinant of the resultant CPO quality. This study collected secondary data on FFB ripeness sortation from a sample of 22 PMO in Riau and North Sumatra, including data for the first and second semesters of 2023, the first semester of 2024, and direct observations during site visits. The RSV, a standard industry metric for FFB quality, indicated that the FFB processed by the sampled PMO in both provinces was generally of good quality, with RSV typically above 85%. Statistical comparison (t-test) of the mean RSV between the two provinces showed no significant difference ($t(26) = -0.617$, $p = 0.55$, based on primary data), suggesting that the FFB grading standards applied at the mills effectively minimised variations arising from diverse cultivation practices (e.g., wet versus mineral soils, independent smallholder versus organised plantations). This is illustrated in Figure 1.

(a)



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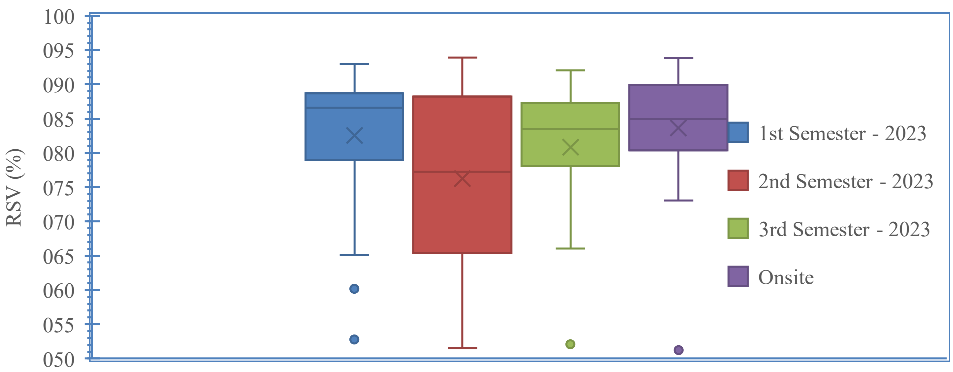

Figure 1. Ripeness Sortation Values (RSV) for 2023 and the 1st semester of 2024 for incoming FFB to sampled Palm Oil Mills in (a) Riau and (b) North Sumatra.

Despite the generally high RSV, the percentage of loose fruits accompanying FFB at the PMO loading ramps in both provinces was observed to be relatively low, typically below 5%. This is noteworthy because an RSV above 85% should ideally correlate with a loose fruit percentage of around 7-8%, potentially approaching 10% at RSV levels above 90%. The low observed loose fruit percentage at conventional and commercial PMO is likely linked to the prevalent practice where FFB that does not meet mill receival standards, along with a significant portion of naturally detached loose fruits, are channelled to numerous smaller, often less formal, mills known as "PMO brondolan" (loose fruit mills). Consultations with the Indonesian Association of Micro, Small, and Medium Palm Oil Mill Entrepreneurs (GAPPKES MIKEMINDO) indicated the existence of 175 such mills in North Sumatra and Riau (114 in Riau, 61 in North Sumatra). These mills specifically process loose fruits and undergrade FFB, which are often purchased at prices attractive to farmers and collectors. This phenomenon also explains the common industry observation where independent smallholders sometimes receive significantly lower prices for their FFB (price disparities reportedly up to IDR 400/kg) compared to plasma or partnered smallholders, as commercial PMO often rationalize purchasing prices based on the actual (lower) loose fruit content and potential oil yield of FFB from unorganised sources. Furthermore, field observations confirmed that harvesters, both in smallholder and some company plantation settings, often retain loose fruits found further from the harvesting circle as a perquisite, thus reducing the loose fruit quantity delivered to the PMO with the FFB. This practice directly impacts the oil extraction rate (OER) at the PMO.

To assess the inherent quality of CPO from diverse FFB sources supplying different types of PMO (e.g., RSPO-certified PMO, conventional PMO with own estates, and PMO without attached plantations relying on market FFB), manual CPO extraction was performed on FFB samples. The results showed variability in inherent CPO quality parameters (FFA, M&I, DOBI) even from FFB sourced from company estates, with some fresh FFB samples yielding CPO with FFA levels around 3%. However, CPO produced from these diverse FFB sources by the respective PMO generally met standard CPO quality specifications. This indicates that PMO, through effective FFB sorting (maintaining high RSV) and subsequent processing adjustments, can largely mitigate the quality variations present in the incoming raw FFB material. Figure 2 illustrates the FFA, M&I, and DOBI values of manually extracted CPO from various FFB sources supplying three different types of PMO.

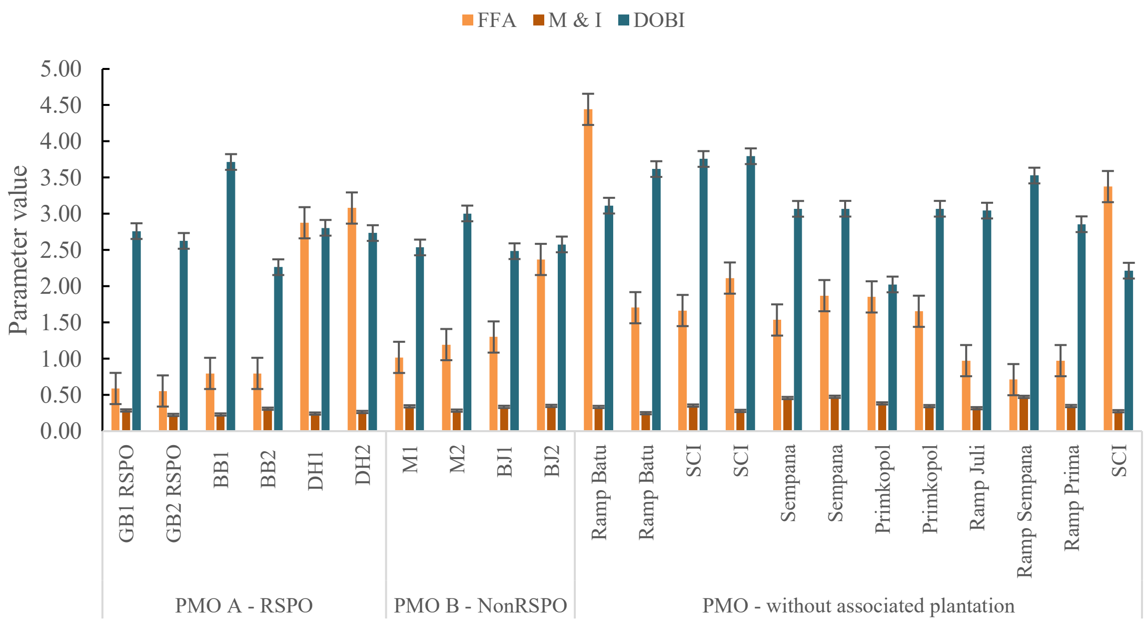

Figure 2. FFA, M&I, and DOBI values of manually extracted oil from various FFB sources supplying three types of PMO: RSPO-certified PMO, conventional PMO, and PMO without associated plantations [orange bars represent FFA, green bars represent DOBI, and red bars represent M&I]

CPO quality dynamics during PMO processing

The study further investigated the changes in key CPO quality parameters at various processing stages within three distinct types of PMO: PMO without an associated plantation (commercial mills), RSPO-certified PMO, and conventional PMO with their own plantations. This aimed to understand how different operational setups manage CPO quality throughout the milling process. An example of a CPO processing flow diagram is provided in Figure 3.

A consistent pattern of FFA content evolution was observed across the different PMO types. Generally, FFA levels tended to increase from the initial FFB harvested to its arrival at the PMO loading ramp due to enzymatic hydrolysis. Even after sterilization, FFA content often continued to rise, attributed to hot water addition during digestion and potential catalytic reactions with metallic equipment surfaces. A notable FFA increase was often recorded at the vibrating screen unit (due to the reintroduction of recovered oil) and within the Continuous Settling Tank (CST) or clarifier, resulting from prolonged oil retention with hot water. While FFA levels tended to decrease in the oil tank and after centrifugal purification, a subsequent increase was often noted in the vacuum dryer, with a significant rise frequently observed in final CPO storage tanks. The typical changes in FFA content at different processing points are illustrated in Figure 4.

Changes in M&I content during PMO processing were generally observed to be less substantial compared to FFA, with a few exceptions. A potential increase in M&I could occur in the CST, where the oil undergoes washing with hot water for several hours. However, any entrained water in the clean oil phase is typically separated at the bottom of the oil tank and is definitively reduced to standard levels in the vacuum dryer. The rate of M&I increase in the storage tank was observed to be relatively slow, provided the tank was well-maintained. These changes are illustrated in Figure 5.

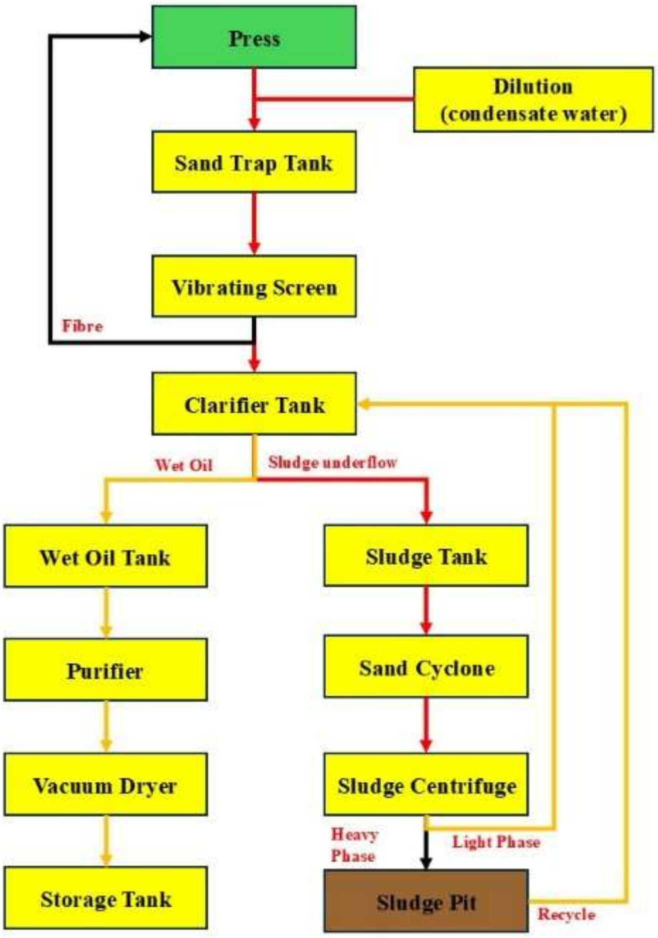

Figure 3. Example flow diagram of CPO processing in a PMO (Foong et al., 2019)

Regarding the DOBI, values generally remained relatively stable during initial processing but tended to decrease up to the screw press stage, likely due to the thermal effects of sterilisation and digestion on carotenoids. Oil purification stages, specifically in the CST and oil tank, often showed an increase in DOBI values, attributed to the removal of oxidised carotenoids and other impurities with the sludge. Subsequently, the drying process in the vacuum dryer typically led to a DOBI reduction due to further heat exposure, and storage in bulk tanks also contributed to a decline. A significant DOBI decrease was particularly noted in the storage tanks of PMO without plantations, linked to blending mainline CPO with lower-quality recycled oil from sludge pits. Figure 6 illustrates the DOBI value changes during processing in the three different PMO types.

Despite these inherent process-induced variations, the study found that all PMO types (commercial, RSPO-certified, and conventional) demonstrated the capability to manage and control final CPO quality parameters such as FFA, M&I, and DOBI to meet specific consumer requirements or contractual agreements. It was particularly noted

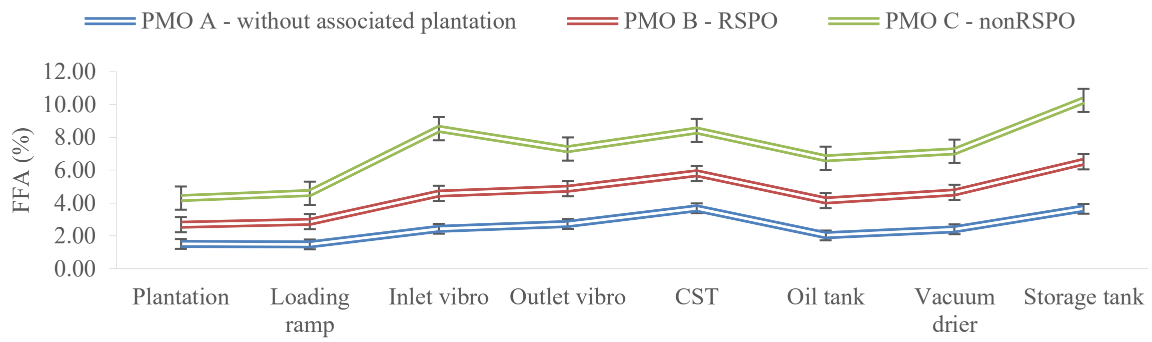

Figure 4. Changes in FFA content during processing in three different types of palm oil mills

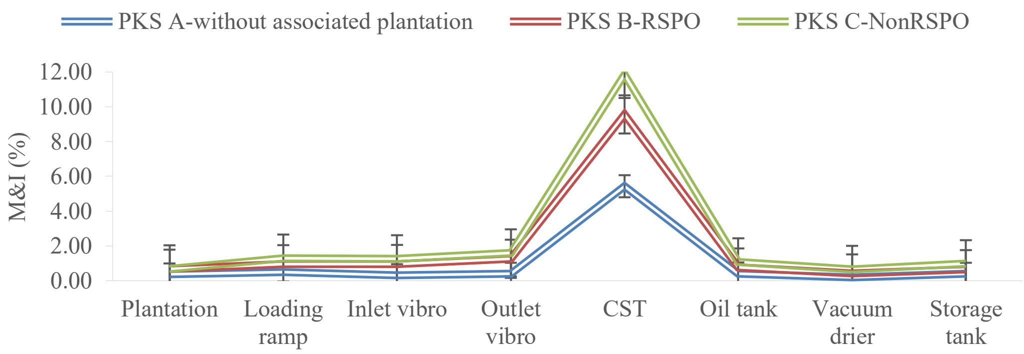

Figure 5. Changes in M&I content during processing in three different types of palm oil mills

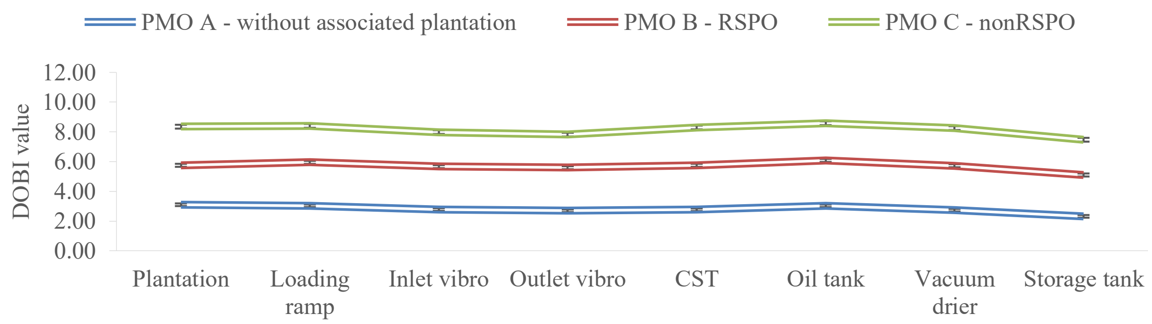

Figure 6. Changes in DOBI values during processing in three different types of palm oil mills

that PMO without plantations, which are often commercial mills, showed a significant DOBI decrease in their storage tanks, linked to the blending of mainline CPO with lower-quality recycled oil from sludge pits. In contrast, PMO with their own plantations and RSPO-certified PMO generally maintained better final CPO quality due to their operational practices. This implies that while all mills can meet standard requirements, operational and waste management practices play a crucial role in preserving the quality and stability of the final product.

Quality changes during cpo transportation and storage: a case study at a major refinery

To investigate CPO quality alterations during transit from PMO and subsequent storage at a refinery, a case study was conducted at a large-scale palm oil refinery located within one of the primary CPO production regions surveyed. This refinery receives CPO feedstock via multiple transportation modes, including road tankers (trucks), rail tank cars, and direct pipeline from an adjacent PMO.

Analysis of management reports from the case study refinery on incoming CPO quality throughout 2024 (as illustrated in Figure 7*)*, revealed trends associated with transport modes. Average monthly FFA content for CPO delivered by truck ranged from 3.81% to 4.33%, which was generally higher than CPO delivered by rail (3.53-4.14%) or pipeline (3.50-4.08%). Conversely, M&I content for pipelined CPO (0.42-0.45%) was slightly higher than for CPO transported by rail (0.35-0.44%) or truck (0.40-0.43%). The DOBI values were relatively consistent across all transport modes, typically ranging from 2.21 to 2.28 for truck deliveries and 2.21 to 2.35 for pipelined CPO. Overall, the incoming CPO, irrespective of transport mode, generally met specifications for regular grade CPO according to SNI 2901:2021 (Badan Standarisasi Nasional, 2021)

Direct sampling and analysis by the research team at the case study refinery provided further insights. An incoming CPO sample (representative of recent deliveries) showed an FFA of 2.97%, M&I of 0.20%, and DOBI of 2.18. A corresponding sample of CPO taken from the refinery's feed tank (i.e., CPO that had undergone storage at the refinery before processing) exhibited an FFA of 3.22%, M&I of 0.21%, and DOBI of 2.19. These figures suggest an increase in FFA content during storage at the refinery, while M&I and DOBI values remained relatively stable during this specific short-term storage observation at the refinery end (Table 1).

Analysis of the CPO samples before and after refinery storage (Table 1) provides further insight into the oil's oxidative state. The PV, an indicator of primary oxidation products, showed a significant increase from 0.75 in the fresh CPO to 2.13 in the CPO from the refinery feed tank. Similarly, the TOTOX value, a measure of total oxidation (primary and secondary products), more than doubled from 3.06 to 5.76. This notable rise in both PV and TOTOX values reinforces the conclusion that oxidative degradation is a key factor affecting CPO quality during logistics and storage. While the AV remained relatively stable, this may be due to the short-term nature of the storage observed in this specific case study. The carotene content, which contributes to the DOBI value, remained fairly consistent at around 475-483 ppm, suggesting that the initial degradation observed was more related to the formation of peroxides rather than a major loss of carotenoids in this specific stage. This finding is consistent with the DOBI values, which, although they showed a decline across the supply chain, did not change significantly during the short-term refinery storage analysis.

A more pronounced change in quality was evident when comparing the CPO quality at the case study refinery with the quality of CPO dispatched from two of its primary supplying PMO. FFA content of CPO dispatched from these PMO during a period close to the sampling at the refinery ranged from 2.32% to 2.98%. This was comparable to, or slightly lower than, the FFA of the incoming CPO sample directly analyzed at the case study refinery (2.97%) but notably lower than the monthly average FFA reported by the refinery (ranging 3.29-3.45% over the preceding 1.5 years). This discrepancy suggests potential FFA increases during transit or could be influenced by the quality of CPO from other, unanalysed PMO supplying the refinery.

The most significant deterioration in quality was observed in the DOBI values. DOBI of CPO dispatched from the two surveyed PMO ranged from 2.65 to 2.87. These values were substantially higher than the DOBI recorded for CPO in the refinery's feed tank (2.19) and also higher than the monthly reported DOBI averages at the case study refinery (2.21-2.35). This considerable decrease in DOBI, from over 2.5 at the PMO to between 2.2 and 2.35 upon arrival and storage at the refinery, strongly indicates oxidative degradation of the oil. This degradation likely occurs during the logistical processes, including transportation and pre-processing handling and storage at the refinery, where factors such as exposure to oxygen, temperature fluctuations, and contact with catalytic surfaces can accelerate oil oxidation.

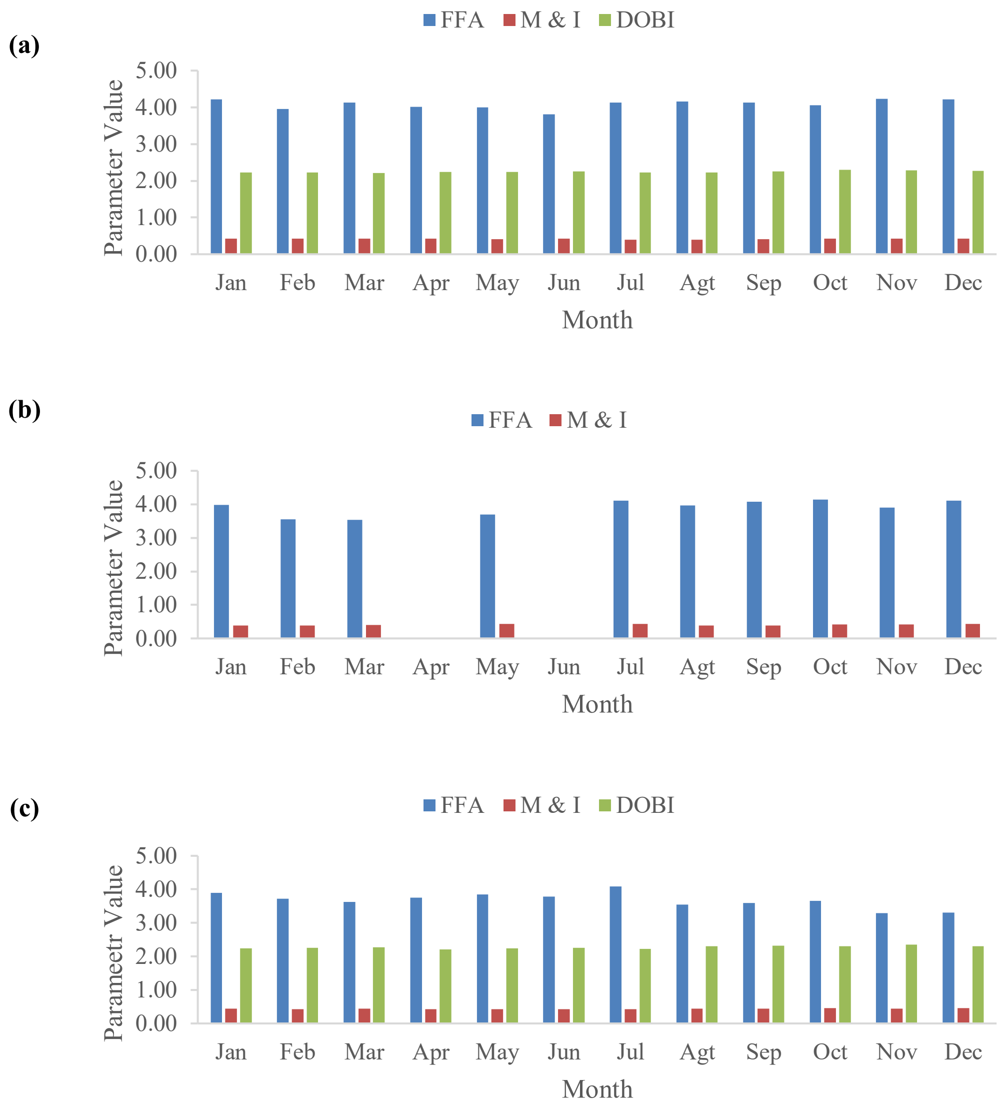

Figure 7. Quality of incoming CPO by different transport modes to the case study refinery, categorized by different transport modes (a) Truck, (b) Train, and (c) Pipeline

Table 1. Analysis of CPO samples before and after refinery storage

Sample	Moisture (%)	Impurities (%)	FFA (%)	PV	AV	TOTOX	DOBI	Carotene (ppm)
CPO fresh	0.20	0.20	2.97	0.75	1.56	3.06	2.18	475.3
CPO feed	0.21	0.06	3.22	2.13	1.51	5.76	2.19	483.7
RBDPO	0.06	1.54	0.39	2.13	0.84	5.09	0.01	1.1
PFAD	0.19	0.98	75.88	2.25	13.24	17.74	0.04	10.1
RBDPS	0.01	0.38	0.52	1.88	nd	nd	0.01	1.6
RBD olein fresh	0.02	1.44	0.51	6.13	0.72	12.97	0.01	1.4
Cooking oil - IV60	0.02	1.45	0.52	1.75	1.06	4.56	0.01	1.4

Notes : CPO = Crude Palm Oil, RBDPO = Refined, Bleached, And Deodorized Palm Oil, PFAD = Palm Fatty Acid Distillate, RBDPS = Refined, Bleached, And Deodorized Palm Stearin, RBD olein fresh = Refined, Bleached, And Deodorized olein fresh.
*nd = not determined

CPO quality specifications and requirements of downstream industries

To understand the specific quality needs and perspectives of the downstream palm oil sector, a FGD was conducted with practitioners from the refining (oleofood), oleochemical, and biodiesel industries, alongside academics and industry associations (e.g., GAPKI). Input was also gathered from relevant government bodies, such as the Ministry of Industry, regarding the future direction of downstream product development, including potential products like Industrial Vegetable/Lauric Oil (IVO/ILO) and Palm Mesocarp Oil. The findings from these interactions are summarised below.

Current practices and awareness at palm oil mills

A general observation from the surveys and discussions was that many PMO operators were not yet fully aligned with the latest Indonesian National Standard for CPO SNI 2901:2021 (Badan Standarisasi Nasional, 2021), which includes the DOBI as a key parameter. Existing sales contracts often still reference specifications similar to the older SNI 2901:2006 (Badan Standarisasi Nasional, 2006), primarily focusing on FFA content (e.g., max 5%) and M&I (e.g., max 0.50%), without explicitly including DOBI or Iodine Value (IV). While most PMO have internal quality standards, DOBI was not commonly used as a routine process control or product quality parameter although some mills reported conducting DOBI analysis upon specific requests for premium CPO contracts, which occasionally offered better pricing. For FFA control, PMO primarily relied on FFB grading at the loading ramp and some mills established internal norms for acceptable FFA increases during processing.

Refining industry (oleofood sector)

The refining industry, producing products like Refined, Bleached, and Deodorized Palm Oil (RBDPO), faces varied quality demands. Specifications often adhere to standards like those from the Palm Oil Refiners Association of Malaysia (PORAM), particularly for industrial consumers or export markets. However, companies producing branded consumer products often implement stricter internal specifications to ensure market acceptability regarding taste, appearance, and shelf life. The oxidative stability of the feedstock CPO is paramount for this sector, as it directly impacts the color, odor, and taste of the refined products. While concerns regarding contaminants like 3-MCPD Esters and Glycidyl Esters (GE) were reported to be somewhat less prominent at the time of the study compared to previous years, refiners acknowledged the ongoing need to be prepared to meet stringent export requirements. A key operational challenge for refiners is the need to adapt their processes to handle incoming CPO of varying quality.

Oleochemical industry

The oleochemical industry utilizes various palm-based feedstocks, including Crude Palm Kernel Oil (CPKO), Refined Bleached Deodorized Palm Stearin (RBDPS), and RBDPO, to produce basic oleochemicals such as fatty acids, glycerine, and soap noodles. As many oleochemical derivatives are used in personal care products, cosmetics, and pharmaceuticals, they are subject to similar stringent regulatory requirements as food products when exported, particularly to markets like Europe. Consequently, the traceability of palm oil feedstock from upstream sources to the oleochemical plant is becoming increasingly important to guarantee product quality and safety. European buyers typically scrutinise for residual pesticides, chlorine, heavy metals, and contaminants like Mineral Oil Saturated Hydrocarbons (MOSH) and Mineral Oil Aromatic Hydrocarbons (MOAH).

Specific CPO quality requirements for this sector include low FFA in the feedstock (CPO or RBDPO), as high FFA can negatively affect the colour, odour, and heat stability of final oleochemical products like fatty acids and refined glycerine. There is also a push for tighter specifications on impurities in CPO (below 0.2%) to minimise contamination risks from metals, MOSH, and MOAH. High Iodine Value, off-colours, and high FFA in the feedstock can also lead to increased processing costs, reduced yields, and potential food safety concerns (including MCPDE & GE if by-products re-enter the food chain or if the oleochemical itself has food-contact applications). For instance, refined glycerol used as a food additive has strict limits for 3-MCPD (e.g., max 0.1 mg/kg under EU Regulation 2023/1329), and maximum levels for MOSH (<20 ppm) and MOAH (<2 ppm) are also applied to various oleochemical products.

Biodiesel industry

In contrast to the oleofood and oleochemical sectors, the biodiesel industry currently does not impose highly specific or stringent quality requirements on its CPO feedstock. Information gathered from feedstock suppliers and industry players, including representatives from GAPPKES MIKEMINDO, indicated that CPO with high FFA content (e.g., 15-35%), such as "minyak brondolan" (oil from loose fruits processed by smaller, often less formal, mills), is readily used as a feedstock for biodiesel production in both North Sumatra and Riau.

The findings from this comprehensive assessment across the CPO supply chain in North Sumatra and Riau highlight a series of interconnected factors that collectively determine the final quality of CPO and its suitability for diverse downstream applications. It is evident that while PMO possess the capability to manage and standardise certain quality parameters, the initial quality of FFB entering the mills, shaped by upstream plantation practices and FFB handling, remains a critical foundational element. The prevalence of the "PMO brondolan" system for processing undergrade FFB and loose fruits, for instance, indicates a systemic response to FFB quality variability at the farm gate, which indirectly influences the feedstock profile received by mainstream PMO and impacts overall oil yield and potentially initial FFA levels.

Within the PMO, specific processing stages, such as sterilization, clarification, and oil drying, were identified as critical points where parameters like FFA, M&I, and DOBI can undergo significant changes. While mills demonstrated an ability to control these parameters to meet basic SNI requirements, the study revealed that internal process management, including the handling of recycled oils, can substantially affect final CPO quality, particularly DOBI. The observed degradation of DOBI values and increase in FFA during transportation and storage, as exemplified by the case study at PT INL, further underscores the vulnerability of CPO quality post-milling. Oxidative degradation during transit and pre-refining storage appears to be a significant challenge, diminishing the quality advantages that might have been achieved at the PMO level.

Juxtaposing these supply chain dynamics with the specific quality requirements of downstream industries reveals potential areas of mismatch and opportunities for optimisation. The refining and oleochemical sectors, particularly those catering to export markets or specialized food applications, demand CPO with high oxidative stability (good DOBI), low FFA, low M&I, and increasingly, specific compositional profiles like low Diacylglycerol (DAG) content. The findings indicated that CPO from North Sumatra, with its generally lower M&I and significantly lower DAG, appeared more aligned with these stringent requirements. Conversely, the biodiesel sector exhibited greater tolerance for CPO with higher FFA. This disparity in needs, coupled with a general lack of full adoption or routine use of advanced quality parameters like DOBI by many PMO, suggests that CPO is not always channelled to its most suitable downstream use, potentially leading to inefficiencies or increased processing costs for downstream players. The limited awareness or practical application of the nuances within the updated SNI 2901:2021 (Badan Standarisasi Nasional, 2021), particularly regarding the functional benefits of 'premium' versus 'regular' grade CPO beyond basic FFA and M&I, further compounds this issue.

Addressing these quality challenges and aligning CPO characteristics with end-user requirements necessitates a multi-pronged approach. This includes promoting best practices at the FFB production level, particularly among smallholders; optimizing PMO processing to preserve inherent oil quality; improving handling, storage, and transportation logistics to minimize degradation; and fostering better communication and understanding between upstream CPO producers and downstream consumers regarding critical quality parameters and their implications.

Conclusion

This study comprehensively investigated the factors influencing CPO quality across the entire supply chain and identified the quality requirements of key downstream industries in North Sumatra and Riau. The findings reveal that CPO quality is shaped at multiple critical stages. While all types of Palm Oil Mills (PMO) demonstrated the capability to meet standard quality requirements for FFA and M&I, the study found a difference in how they manage and influence CPO quality. PMO without associated plantations, for instance, showed a significant DOBI degradation in their storage tanks due to blending CPO with lower-quality recycled oil. In contrast, PMO with their own plantations and RSPO-certified PMO generally maintained better final CPO quality and oxidative stability due to their operational practices. A clear correlation was established between CPO quality and downstream demands. The refining and oleochemical sectors require high oxidative stability (good DOBI) and low FFA content to ensure the quality and safety of final products. The study found CPO with lower M&I, such as that from North Sumatra, to be more aligned with these stringent requirements. Conversely, the biodiesel sector is more tolerant and readily uses CPO with high FFA, demonstrating a less stringent quality requirement. The most significant quality deterioration was found to occur post-milling, during CPO transportation and storage. This phase is critical for quality loss, as the study highlights a substantial DOBI degradation and FFA increase. This degradation is primarily caused by oxidation and hydrolysis during logistics and pre-refining storage. In conclusion, this research underscores the vulnerability of CPO quality throughout its journey and highlights a clear need for integrated strategies. These strategies should encompass improved FFB handling, optimized

PMO processing to preserve inherent quality, and enhanced logistics to minimize post-milling degradation. This integrated approach is crucial for improving the overall efficiency and competitiveness of the Indonesian palm oil industry.

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