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Analysis of Oil Losses in Press Cake Using Fault Tree Analysis (FTA) in Crude Palm Oil (CPO) Processing Industry

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Abstrak

Kehilangan minyak dalam pengolahan Crude Palm Oil (CPO) merupakan indikator kualitas dan ekonomi yang kritis bagi pabrik kelapa sawit. Penelitian ini mengkaji akar penyebab kehilangan minyak berlebih pada press cake (serat) di stasiun pengempaan PT. Perkebunan Nusantara IV Regional I PKS Sei Meranti, yang mengolah 45 ton Tandan Buah Segar (TBS) per jam. Selama bulan Januari 2026, rata-rata kehilangan minyak pada press cake yang tercatat adalah 3,86%, melebihi standar perusahaan sebesar 3,70%. Pendekatan Fault Tree Analysis (FTA) digunakan untuk mengidentifikasi dan menganalisis secara sistematis kejadian-kejadian kegagalan yang berkontribusi. Kejadian puncak "kehilangan minyak berlebih pada ampas press" diuraikan menjadi empat kategori kejadian antara, yaitu sumber daya manusia, kondisi mesin, kualitas bahan baku, dan metode kerja. Analisis mengidentifikasi sepuluh kejadian dasar sebagai akar penyebab, meliputi ketidakpatuhan operator terhadap SOP, tidak adanya perawatan preventif, tandan buah mentah akibat sterilisasi yang tidak memadai, serta penyimpangan pada pengaturan tekanan hidrolik dan suhu. Dari 24 hari produksi yang dianalisis, 18 titik data (75%) dinyatakan di luar kendali berdasarkan batas kendali yang telah ditetapkan. Diagram pohon disusun untuk mengusulkan tindakan korektif yang menjawab setiap kategori akar penyebab. Temuan penelitian ini memberikan rekomendasi yang dapat ditindaklanjuti untuk mengurangi kehilangan minyak dan meningkatkan efisiensi ekstraksi CPO secara keseluruhan.

Kata Kunci: Kehilangan Minyak; Fault Tree Analysis; Minyak Sawit Mentah; Ampas Press; Screw Press; Pabrik Kelapa Sawit

Abstract

Oil losses in Crude Palm Oil (CPO) processing represent a critical quality and economic indicator for palm oil mills. This study investigates the root causes of excessive oil losses in press cake (fibre) at the pressing station of PT. Perkebunan Nusantara IV Regional I PKS Sei Meranti, which processes 45 tonnes of Fresh Fruit Bunches (FFB) per hour. During Januray 2026, the average press cake oil losses recorded were 3.86%, exceeding the company standard of 3.70%. A Fault Tree Analysis (FTA) approach was employed to systematically identify and analyse contributing failure events. The top event "excessive press cake oil losses" was decomposed into four intermediate event categories human resources, machine condition, raw material quality, and work method. The analysis identified ten basic events as root causes, including operator non-compliance with SOPs, absence of preventive maintenance, underripe fruit bunches due to inadequate sterilization, and deviations in hydraulic pressure and temperature settings. Out of 24 production days analysed, 18 data points (75%) were found to be out-of-control based on the established control limits. A tree diagram was constructed to propose corrective actions addressing each root cause category. The findings provide actionable recommendations for reducing oil losses and improving overall CPO extraction efficiency.

Keywords: Oil Losses; Fault Tree Analysis; Crude Palm Oil; Press Cake; Screw Press; Palm Oil Mill

1. Introduction

The palm oil industry constitutes a fundamental pillar of Indonesia's agricultural economy, with the country ranking among the world's largest producers of Crude Palm Oil (CPO). Palm Oil Mills (PKS) are complex industrial facilities that transform Fresh Fruit Bunches (FFB) through a series of mechanical and thermal processes to extract CPO and palm kernel oil. The economic viability of these operations is critically dependent on maximising oil extraction efficiency while minimising process losses.

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Oil losses defined as the quantity of oil that should theoretically be recovered from FFB processing but is instead lost during the extraction process represent one of the most significant challenges in palm oil mill operations. These losses occur across multiple processing stations, including the sterilizer, thresher, pressing station, and clarification unit [1]. In economic terms, even marginal reductions in oil loss percentage translate into substantial revenue gains given the large throughput volumes of modern palm oil mills.

The pressing station is particularly critical as it is responsible for the mechanical extraction of oil from the digested fruit mesocarp. Screw press machines apply hydraulic pressure to separate oil from the fibrous press cake, and the residual oil content in this press cake directly determines the pressing efficiency. Industry benchmarks and company standards typically set maximum acceptable oil losses in press cake at approximately 3.5-4.0% [2,3].

PT. Perkebunan Nusantara IV Regional I PKS Sei Meranti, a state-owned palm oil processing enterprise in North Sumatra, Indonesia, established an internal standard of 3.70% maximum oil losses for press cake. However, operational data collected during January 2026 revealed an average oil loss of 3.86%, with 75% of production days recording values exceeding this threshold. This systematic deviation from quality standards necessitated a rigorous root cause analysis.

Fault Tree Analysis (FTA) is a top-down, deductive reliability analysis methodology originally developed by H.A. Watson at Bell Laboratories in 1961 and subsequently adopted across industries for safety and quality management applications [4]. FTA employs a hierarchical logical structure using AND/OR gates to trace the propagation of failures from basic causal events to top-level undesired outcomes. In manufacturing and process industries, FTA has demonstrated effectiveness in identifying both technical and human-factor contributions to quality failures [5,6].

The production of CPO involves a sequential series of operations beginning with the receipt and sorting of FFB at the weighbridge and reception station [7]. Fruit bunches are subsequently loaded into sterilizer vessels where high-pressure steam (2.8-3.0 kg/cm²) is applied in a triple-peak cycle to soften fruit, loosen fruitlets from bunches, inactivate lipase enzymes, and condition the mesocarp for efficient oil extraction [8] Following sterilization, bunches enter the threshing station where rotating drums separate individual fruitlets from the empty fruit bunches (EFB). Digestion precedes pressing, during which fruitlets are macerated in heated vessels to disrupt oil-bearing cells and achieve a pulp temperature of 90-95°C. The digested mash is then fed to screw press machines operating at hydraulic pressures of 35-55 bar [3,9].

Oil losses in palm oil mills are categorized according to their point of occurrence within the process. Nurrahman et al. identified five primary loss streams: (1) condensate losses from the sterilization station, (2) EFB losses from the threshing station, (3) press cake losses from the pressing station, (4) shell/nut losses, and (5) sludge losses from the clarification station. Among these, press cake oil losses are generally the most significant and technically controllable through machine and process optimization. Factors influencing press cake oil losses include the maturity and composition of incoming FFB, the effectiveness of sterilization, digester temperature and retention time, screw press hydraulic pressure settings, and the mechanical condition of press components [10,11].

This paper presents a comprehensive FTA-based investigation of excessive oil losses in press cake at PKS Sei Meranti, with the objectives of (1) quantifying the extent and pattern of press cake oil losses relative to established standards (2) constructing a fault tree model to identify all contributing root causes and (3) developing systematic corrective action recommendations to restore and sustain compliance with quality standards.

2. Research Methods

2.1. Research Setting and Data Collection

This study was conducted at PT. Perkebunan Nusantara IV Regional I PKS Sei Meranti, a palm oil processing facility in North Sumatra, Indonesia, with a rated processing capacity of 45 tonnes FFB/hour. Data collection was performed during the period of 1-30 January 2026, yielding a dataset of 24 production days (6 days were non-operational due to equipment breakdowns). Oil losses measurements were obtained from the mill's quality control laboratory, where samples are routinely analysed every two hours during production. Laboratory analyses quantified four oil loss parameters: sterilizer condensate oil losses, EFB oil losses, press cake oil losses, and nut/shell oil losses. All values are expressed as percentage oil on wet basis (% o.w.b.). Field observations and operator interviews were conducted to supplement quantitative data with qualitative insights into operational practices.

2.2. Statistical Process Control Analysis

Statistical process control (SPC) was applied to press cake oil losses data to assess process stability and identify out-of-control conditions. Control chart limits were established using the company standard as the upper control limit (UCL = 3.70%) and a lower control limit (LCL = 3.00%). Data points exceeding UCL were classified as out-of-control, indicating assignable causes requiring investigation.

2.3. Statistical Process Control Analysis

The FTA was constructed following a structured four-step procedure: (1) definition of the top event as 'excessive oil losses in press cake; (2) identification of intermediate event categories through expert consultation and process review; (3) decomposition of intermediate events to basic events using field observations, maintenance records, and operator interviews; and (4) logical connection of events using appropriate Boolean gates. The FTA was validated through expert review by mill management and quality control personnel. Following FTA construction, a tree diagram was developed to systematically map corrective action recommendations to each identified root cause category. This tool organizes solutions hierarchically from strategic objectives through tactical measures to specific operational actions, providing a practical roadmap for implementation.

3. Research Methods

3.1. Oil Losses Performance Overview

Table 1 presents the company established maximum standards for each oil loss parameter alongside the monthly averages for January 2026. The data reveal that press cake oil losses consistently and substantially exceeded the established standard throughout the monitoring period.

Table 1. CPO Oil Losses Standard

No.	Oil Loss Parameter	Max. Standard (%)	Avg. Actual (%)	Status
1	Sterilizer Condensate	0.70	0.68	Within Norm
2	Empty Fruit Bunch (EFB)	1.80	1.28	Within Norm
3	Press Cake (Fibre)	3.70	3.86	Exceeded
4	Shell/Nut	0.80	0.75	Within Norm

As shown in Table 1, three of the four oil loss parameters (sterilizer condensate, EFB, and shell/nut losses) recorded average values within company norms during the monitoring period. However, press cake oil losses averaged 3.86%, representing a 4.3% exceedance above the 3.70% standard. This excess, while appearing modest in percentage terms, translates to significant cumulative oil recovery losses given the mill's 45 t/hour processing capacity.

3.2. Press Cake Oil Losses - Detailed Analysis

Table 2 presents the daily press cake oil losses data for the 24 production days in January 2026. The data demonstrate considerable day-to-day variability, with values ranging from a minimum of 3.41% (7 January) to a maximum of 4.20% (28 January). Notably, the lowest recorded value (3.41%) still falls above the lower acceptable boundary, while the majority of readings cluster in the 3.80-4.20% range, consistently above the 3.70% standard.

Table 2. Daily Oil Losses Data

No	Tanggal	*Concensate* (%)	EFB (%)	Press Cake (%)	Nut (%)	Status
1	01/01/2026	0.69	1.73	4,13	0,91	Exceeded
4	04/01/2026	0.78	1.67	3.90	0.77	Exceeded
5	05/01/2026	0.56	1.78	3.62	0.89	Within Norm
7	07/01/2026	0.84	1.22	3.41	0.72	Within Norm
8	08/01/2026	0.66	0.86	3.88	0.65	Exceeded
9	09/01/2026	0.58	1.77	3.87	0.68	Exceeded
10	10/01/2026	0.71	1.10	3.82	0.78	Exceeded
11	11/01/2026	0.70	1.23	3.98	0.64	Exceeded
12	12/01/2026	0.63	0.84	3.85	0.63	Exceeded
13	13/01/2026	0.59	0.81	3.85	0.81	Exceeded
14	14/01/2026	0.68	0.78	3.79	0.66	Exceeded
15	15/01/2026	0.82	1.27	3.66	0.59	Within Norm
16	16/01/2026	0.66	1.32	3.69	0.92	Within Norm
18	18/01/2026	0.68	0.99	3.50	0.77	Within Norm
19	19/01/2026	0.87	0.82	3.72	076	Exceeded
20	20/01/2026	0.66	1.22	3.49	0.65	Within Norm
23	23/01/2026	0.71	0.88	4.15	0.81	Exceeded
24	24/01/2026	0.67	1.36	4.11	0.71	Exceeded
25	25/01/2026	0.63	1.32	4.09	080	Exceeded
26	26/01/2026	0.67	1.92	4.03	0.69	Exceeded
27	27/01/2026	0.53	1.67	3.96	0.64	Exceeded
28	28/01/2026	0.68	1.31	4.20	0.87	Exceeded
29	29/01/2026	0.72	0.87	4.00	0.85	Exceeded
30	30/01/2026	0.60	1.92	3.99	0.79	Exceeded
Average		**0.68**	**1.28**	**3.86**	**0.75**	-
Standard		**0.70**	**1.80**	**3.70**	**0.80**	-

3.3. Statistical Process Control Chart

A large proportion of the data (75%) exceeds the upper control limit of 3.70%, indicating the presence of assignable causes rather than random variation. The process mean of 3.86% is also above this limit, confirming that the process is not in a state of control. An increasing pattern of oil losses is observed toward the end of the monitoring period, suggesting possible machine wear or performance degradation. In contrast, the lower values at the beginning of the period support the assumption of gradual deterioration over time as the equipment continues to operate.

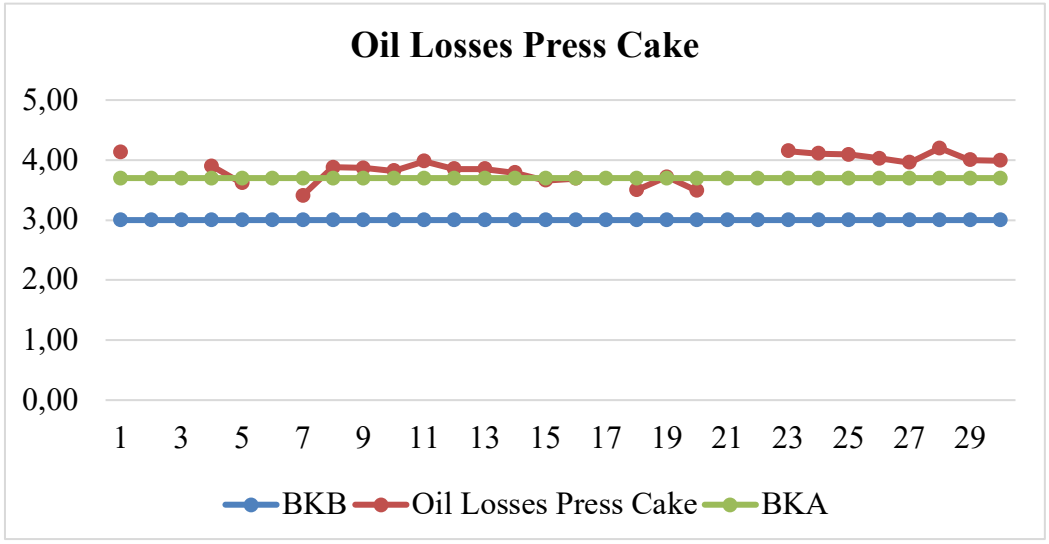

Fig 1. Oil Losses Control Map of Press Cake

3.4. Fault Tree Analysis

The FTA diagram for press cake oil losses at PKS Sei Meranti identifies the top event excessive oil losses in press cake as resulting from OR connected intermediate event categories representing four causal domains: Human Resources (SDM), Machine Condition, Raw Material Quality, and Work Method. Each intermediate category was further decomposed to basic events representing specific, observable failure conditions.

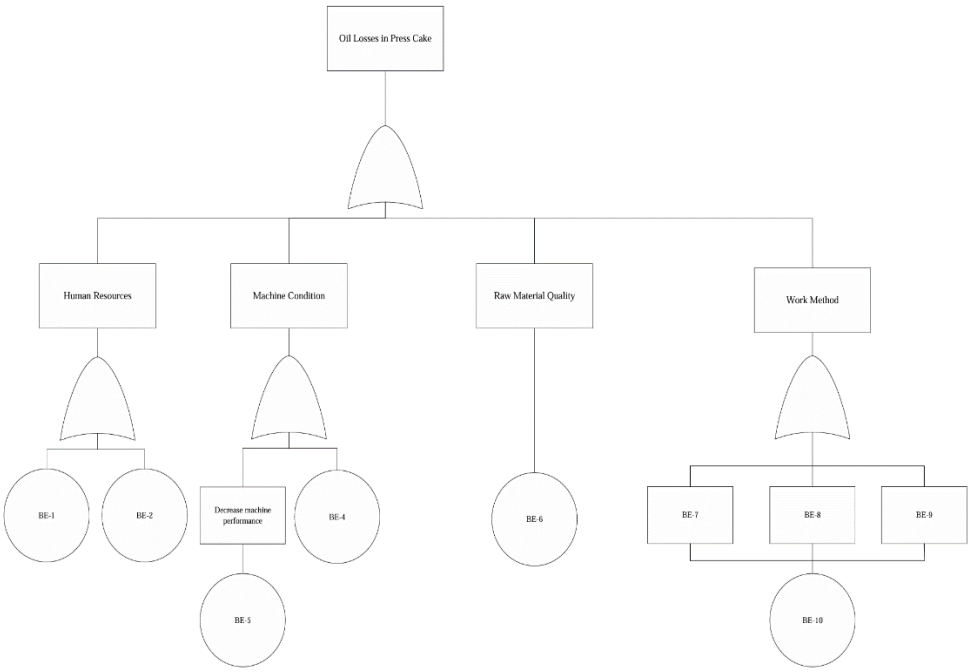

Fig 2. Fault Tree Analysis Diagram

The basic events identified through the FTA are summarized in Table 3, organized by their intermediate event category. The OR gate connecting the four intermediate categories to the top event indicates that any single category, independently, is sufficient to produce excessive oil losses a finding that underscores the multi-causal nature of the problem and the need for simultaneous interventions across all categories.

Table 3. Basic Event Identified Through Fault Tree Analysis

Category	Basic Event	Gate	*Description*
Human Resources	BE-1	OR	Operator non-compliance with SOP during press machine operation
	BE-2	OR	Insufficient attention to machine capacity monitoring and adjustment
Machine Condition	BE-3	OR	Decreased machine performance due to worn/malfunctioning components
	BE-4	OR	Reactive breakdown maintenance approach causing performance gaps
	BE-5	OR	Press machine components (worm screw) operating below specification
Raw Material	BE-6	OR	Underripe FFB entering press station due to inadequate sterilization
Work Method	BE-7	OR	Press machine operated below rated capacity, reducing extraction pressure
	BE-8	OR	Temperature deviating from norm (80-90°C), affecting oil viscosity
	BE-9	OR	Hydraulic pressure deviating from norm (35-40 bar), reducing press force
	BE-10	OR	Operator work practices deviating from established SOP procedures

3.5. Root Cause Discussion

Human Resources. Human factor contributions were identified through two basic events (BE-1 and BE-2). Operator non-compliance with SOPs during press operation (BE-1) manifests in improper feeding rates, failure to monitor pressure gauges, and insufficient attention to press cake consistency. These behavioural deviations are compounded by inadequate monitoring of machine capacity utilization (BE-2), which prevents operators from making timely adjustments when pressing conditions deviate from optimal parameters. Human factor contributions account for approximately 30-40% of oil loss exceedances in Indonesian palm oil mills [12].

Machine Condition. Three machine-related basic events (BE-3, BE-4, BE-5) were identified. Progressive wear of screw press components, particularly the worm screw, press cone, and drainage cage perforations, directly reduces pressing effectiveness (BE-3, BE-5). The mill's reliance on reactive breakdown maintenance (BE-4) means that component degradation is not addressed until failure occurs, resulting in extended periods of sub-optimal performance.

Raw Material Quality. Underripe FFB (BE-6) represents a significant upstream cause of press cake oil losses. Inadequate sterilization -whether due to insufficient steam pressure, shortened cooking time, or improper scheduling -results in fruit mesocarp that is incompletely softened. This incomplete softening impairs digestion effectiveness and reduces the liberation of oil from mesocarp cells prior to pressing [13]. The temporal correlation between periods of higher oil losses (late January) and maintenance shutdowns earlier in the month suggests that post-shutdown FFB accumulation may have introduced batches with uneven maturity profiles.

Work Method. Four work method-related basic events (BE-7 through BE-10) were identified. Operating the press below rated capacity (BE-7) reduces the back pressure required for effective oil extraction, as the press cage is insufficiently packed to generate optimal compression. Temperature deviations (BE-8) from the 80-90°C norm affect oil viscosity; temperatures below the lower bound increase oil viscosity and reduce drainage through press cage perforations. Hydraulic pressure deviations (BE-9) below the 35-40 bar specification directly reduce the mechanical force applied to the digested mash, resulting in incomplete oil expression. These method deficiencies are often interrelated and collectively exacerbated by operator SOP non-compliance (BE-10) [14,15]

3.6. Proposed Corrective Analysis

Based on the FTA findings, a tree diagram was constructed to systematically map corrective actions to each root cause category. Table 4 presents the structured corrective action recommendations, organized by causal category, strategic intervention, tactical measure, and specific operational action.

Table 4. Structured Corrective Action Recommendation Based on FTA Diagram

Category	Strategic Intervention	*Tactical Measure*	*Specific Action*
Human Resources	Enhance operator competency	Structure training and incentive program	Conduct SOP refresher training quarterly and implement performance based incentives
		Performance monitoring system	Introduce shift-level check sheets to record key parameters (pressure, temperature, throughput)
Machine Condition	Implement preventive maintenance	Scheduled inspection and manintenance	Establish a monthly preventive maintenance (PM) schedule
		Component repair and replacement	Replace worn worm screws when clearance exceeds 5 mm and maintain spare parts availability

Raw Material	Improve sterilization quality control	Enhanced sterilizer process monitoring	Install digital temperature and pressure loggers on sterilizers with automated recording system
		Fruit maturity surveillance	Strengthen incoming FFB sorting to reject low quality raw materials (<5% loose fruit bunches)
Work Method	Standardized pressing operational parameters	Real time process parameter monitoring	Install digital pressure gauges and temperature indicators at each press unit
		SOP improvement and enforcement	Revise pressing SOP to specify minimum feed rate (≥80% of rated capacity)

4. Conclusion

Perkebunan Nusantara IV Regional I PKS Sei Meranti during January 2026. The principal findings and conclusions are as follows: • Press cake oil losses averaged 3.86% during the monitoring period, exceeding the company standard of 3.70% by 0.16 percentage points. Statistical process control analysis confirmed that 75% (18/24) of production days were out-of-control, indicating systematic rather than random causation.

The FTA identified ten basic events distributed across four causal categories: human resources (2 events), machine condition (3 events), raw material quality (1 event), and work method (4 events). All intermediate categories were connected to the top event through OR gates, confirming multi-causal aetiology.

Machine condition emerged as the most critical causal domain, evidenced by the temporal trend of increasing oil losses over the monitoring period consistent with progressive component wear. The absence of a structured preventive maintenance programme was identified as a fundamental systemic weakness.

The tree diagram-based corrective action framework provides actionable recommendations across all causal categories, with estimated potential for reducing press cake oil losses to within the 3.70% standard through simultaneous implementation of proposed interventions. Future research directions include quantitative probability estimation for FTA basic events using historical maintenance and production data, integration of FTA findings with Failure Mode and Effect Analysis (FMEA) for risk prioritization, and longitudinal evaluation of oil loss performance following implementation of the recommended corrective actions.

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