Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications

Loso Judijanto*

IPOSS Jakarta, Indonesia

Abstract

The oil palm industry represents a critical component of global vegetable oil production, with Indonesia and Malaysia accounting for over 85% of the world's supply. However, significant economic losses persist due to non-optimal harvesting practices, particularly the premature or delayed harvesting of fresh fruit bunches (FFB). This qualitative literature review synthesizes evidence from 2020 to 2026 to examine the economic costs associated with harvesting FFB at suboptimal maturity levels and their implications for production quality and quantity. Through thematic analysis of peer-reviewed literature, industry reports, and institutional publications, this study identifies optimal maturity parameters (23-24 weeks after anthesis, oil content >40%, DOBI >3.0) and quantifies multi-level economic impacts. Findings reveal that under-ripe harvesting reduces oil extraction rates (OER) from an optimal 20-23% to 9.5-15%, while over-ripe harvesting accelerates free fatty acid (FFA) formation at 0.1% per 24 hours and increases loose fruit losses (3-7% of production). National-scale economic losses are substantial, with Malaysia experiencing approximately RM 4.2 billion annually and Indonesia facing similar magnitude impacts. Post-harvest losses account for 5.21% of total production, with quality penalties ranging from 300 to 500 IDR/ton. This review synthesizes mechanisms of economic loss across biochemical, operational, and market levels, highlighting the critical importance of maturity optimization for industry competitiveness and smallholder welfare. Recommendations emphasize strict adherence to maturity standards, the implementation of transparent, quality-based pricing systems, technological interventions to enable objective maturity detection, and capacity-building programs for smallholder communities. The findings underscore that optimal harvesting practices represent a low-cost, high-impact pathway to enhancing the sustainability and economic viability of the oil palm industry.

JEL Classification

Q13 (Agricultural Markets and Marketing), Q16 (R&D; Agricultural Technology), Q18 (Agricultural Policy), O13 (Economic Development: Agriculture)

Introduction

Background

The oil palm (*Elaeis guineensis* Jacq.) industry occupies a pivotal position in the global vegetable oil market, with crude palm oil (CPO) serving as the world's most consumed and traded edible oil. Indonesia and Malaysia collectively dominate global production, contributing approximately 85% of the world's palm oil supply, with Indonesia alone producing over 47 million tonnes annually as of 2025. The strategic economic significance of this industry extends beyond national GDP contributions to encompass livelihoods for

millions of smallholder farmers, employment generation across value chains, and foreign-exchange earnings crucial to economic development [1-3].

Fresh fruit bunches (FFB) constitute the fundamental raw material for CPO production, with their quality and maturity status serving as primary determinants of both extraction efficiency and final product quality. The relationship between FFB maturity and oil content follows a well-documented physiological trajectory, wherein oil accumulation in the mesocarp tissue progresses systematically during fruit development, reaching maximum concentrations at optimal ripeness. The Malaysian Palm Oil Board (MPOB) has established standardized maturity classifications—under-ripe, partially ripe, ripe, and over-ripe—based on visual characteristics and biochemical parameters, providing industry benchmarks for harvest timing decisions [4].

Despite established standards and widespread recognition of the importance of maturity, suboptimal harvesting practices persist across producing regions, with significant proportions of FFB harvested either prematurely or beyond optimal maturity windows. The prevalence of non-optimal harvesting stems from multiple intersecting factors, including labor constraints, economic pressures favoring volume over quality, limitations in subjective visual assessment methods, and information asymmetries particularly affecting smallholder operations. These practices generate substantial economic costs through dual mechanisms: quantitative losses from reduced oil extraction rates and qualitative degradation that affects market prices and processing efficiency [5,6].

Research Urgency

The economic magnitude of non-optimal FFB harvesting extends from individual farm-level productivity losses to national-scale economic impacts. Conservative estimates for Malaysia indicate annual losses of RM 2.26 billion (approximately USD 538 million) attributable to harvesting a single under-ripe bunch per palm cycle, with an additional RM 1.55 billion (USD 370 million) lost through uncollected loose fruits from over-ripe bunches. Indonesian estates face comparable challenges, with documented annual losses of IDR 2.18 billion at the individual plantation level for flat-terrain operations alone. These figures represent substantial opportunity costs in an industry where profit margins are increasingly compressed by rising production costs and volatile international commodity prices [7-9].

Beyond direct production losses, quality implications carry significant economic ramifications throughout value chains. Oil extraction rate (OER) variations driven by maturity status directly impact profitability, with the differential between under-ripe FFB (9.5% OER) and optimally ripe material (20-23% OER)

representing more than doubling of oil yield from equivalent biomass inputs. Quality parameters, including free fatty acid (FFA) content, deterioration of bleachability index (DOBI), and carotene concentrations, affect CPO market grades, with price differentials ranging from 300-500 IDR per ton based on quality classifications. For smallholder farmers, who constitute approximately 40% of Indonesia's oil palm area, these quality premiums and penalties significantly influence household incomes and economic welfare [10,11].

The persistence of yield gaps between actual and potential production further underscores the urgency for addressing harvest optimization. Current Indonesian smallholder yields average 13.1 tonnes FFB/ha/year, with independent smallholders achieving 40% below good agricultural practice benchmarks. While multiple agronomic factors contribute to these gaps, harvest timing and post-harvest handling represent controllable variables with immediate implementation feasibility and rapid returns on investment [12].

Research Objectives

This qualitative literature review pursues three interconnected objectives. First, to synthesize current scientific understanding of optimal FFB maturity parameters and their physiological foundations, establishing evidence-based benchmarks for harvest timing decisions. Second, to comprehensively analyze and quantify the economic implications of non-optimal harvesting across quality and quantity dimensions, mapping loss mechanisms from biochemical processes through market transactions. Third, to identify determinants of suboptimal practices and to evaluate potential intervention pathways to enhance maturity optimization across diverse production contexts.

By addressing these objectives through systematic synthesis of recent literature (2020-2026), this review aims to provide actionable intelligence for multiple stakeholder groups: farmers and plantation managers seeking productivity enhancement strategies, mill operators designing quality-based procurement systems, policymakers developing industry support programs, and researchers identifying critical knowledge gaps requiring further investigation.

Literature Review

Conceptual Framework of Optimal FFB Maturity

The physiological maturation of oil palm fruits follows a precisely orchestrated developmental sequence, typically spanning 22-26 weeks from anthesis to full ripeness, with optimal harvest windows centering on 23-24 weeks after anthesis (WAA). During this developmental trajectory, the mesocarp tissue undergoes dramatic biochemical transformations, with oil content increasing

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 2/14

from negligible levels (<5% fresh weight) in immature fruits to exceeding 40% at optimal maturity. This lipid accumulation occurs concomitantly with systematic moisture reduction, in which water content declines from approximately 72.69% at 19 WAA to 26.84% at 23 WAA, creating inverse relationships between moisture and oil concentrations that serve as fundamental maturity indicators [13].

MPOB standards provide operational definitions for maturity classifications based on observable characteristics. Under-ripe bunches exhibit predominantly green or yellow-green coloration with minimal loose fruit detachment (0-2 fruits), while ripe bunches display characteristic reddish-orange outer fruit coloration with moderate loose fruit presence (5-10 fruits). Over-ripe status manifests as extensive loose fruit detachment (>15 fruits), darkened coloration, and easy shedding, indicating progression beyond optimal harvest timing. These visual criteria, while widely implemented, demonstrate inherent subjectivity and inter-observer variability, motivating research into objective assessment technologies [14].

Varietal characteristics significantly influence maturity parameters and oil yield potential. The predominant Tenera hybrid (Dura × Pisifera cross) exhibits superior oil-to-bunch ratios compared to thick-shelled Dura varieties, with mesocarp-to-fruit ratios of 80-90% enabling higher extraction efficiencies when harvested at optimal maturity. These genetic differences underscore the importance of variety-specific maturity assessment protocols and harvest scheduling systems [15].

Biochemical and Physical Maturity Indicators

Oil content progression represents the most economically consequential maturity parameter, following sigmoid accumulation kinetics throughout fruit development. Research by Hasibuan (2020) documented oil content evolution from 19.84% at the under-ripe stage to 42.63% at full ripeness, representing more than doubling of extractable oil per unit fruit mass. This accumulation reflects mesocarp cell differentiation, during which plastids transform into oil-storing organelles through coordinated expression of fatty acid biosynthesis pathways [15,16].

Pigment compositions provide reliable biochemical signatures of maturity status with direct quality implications. β-carotene concentrations increase dramatically during ripening, from 175 mg/kg in underripe fruits to 762 mg/kg at optimal maturity, which is responsible for the characteristic orange-red coloration of ripe bunches. Conversely, chlorophyll content declines systematically, from 5.38 mg/kg in immature fruits to near-baseline levels in fully ripe material. These pigment transitions enable non-destructive maturity assessment through spectroscopic methods, with Raman

Free fatty acid (FFA) formation, while not strictly a maturity indicator, becomes critically important in overripe fruits, where lipase enzyme activation accelerates the hydrolytic degradation of triglycerides. Baseline FFA content remains low (<2.5%) in freshly harvested ripe FFB but increases at approximately 0.1% per 24 hours post-harvest, with over-ripe fruits exhibiting accelerated formation rates. Mechanical damage from loose fruit detachment and prolonged field exposure exacerbates FFA formation, creating quality deterioration cascades that reduce CPO value [19].

Theoretical Framework of Economic Implications

Production function theory provides conceptual foundations for understanding the impacts of maturity on economic outcomes. In this framework, FFB maturity serves as a quality-adjusted input variable, while OER represents the transformation function that converts raw material into marketable output. The non-linear relationship between maturity and oil yield—where small deviations from optimal timing yield disproportionate reductions in output—creates economic incentives for precision in harvest scheduling [20].

The concept of yield gaps, defined as the difference between potential and actual production, provides an analytical lens for quantifying the opportunity costs of non-optimal practices. Observed yield gaps in oil palm systems range from 40-60% below biological potential, with harvest timing and post-harvest handling contributing substantially to these differentials. Economic valuation of these gaps requires an integrated assessment of both quantity losses (reduced OER) and quality penalties (price discounts), as these dimensions interact multiplicatively rather than additively [21].

Quality, premium, and discount pricing mechanisms in palm oil markets create direct financial incentives for maturity optimization. The MPOB reference pricing system, implemented in July 2020, establishes transparent linkages between OER and FFB prices, with payments calculated on a 1% OER basis. This structure theoretically aligns farmer incentives with mill requirements, though implementation challenges persist, particularly for smallholders selling through intermediaries who may not fully transmit quality signals. Price differentials of 300-500 IDR per ton between quality grades translate to substantial annual income variations for producing households [22].

Post-harvest loss economics encompasses multiple categories of loss across the value chain. Field losses from unharvested bunches and uncollected loose fruit represent foregone production that never enters processing channels. Collection point and transport losses stem from handling damage and time delays between harvest and processing. Mill-level sorting rejections of

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 3/14

substandard FFB constitute quality-based losses where material enters but generates reduced value. A comprehensive economic assessment requires aggregating these multi-stage losses while accounting for their interdependencies [23].

Methods

Research Approach

This study employs qualitative literature review methodology, distinguished from systematic review approaches by its interpretive synthesis orientation and thematic rather than strictly protocol-driven analysis. Qualitative literature reviews enable comprehensive exploration of complex phenomena in which research questions span multiple disciplines, methodologies, and knowledge domains, making them particularly appropriate for investigating the economic costs of agricultural practices that intersect agronomy, biochemistry, operations management, and market economics [24,25].

The philosophical foundation rests on interpretivist epistemology, recognizing that understanding of economic impacts emerges through synthesis of diverse evidence types—quantitative production data, biochemical measurements, market price observations, and qualitative accounts of farmer decision-making. This approach facilitates the integration of heterogeneous evidence sources while maintaining analytical rigor through systematic procedures for literature identification, evaluation, and synthesis [26,27].

Literature Search Strategy

Literature identification employed multi-database search strategies across academic repositories (Scopus, Web of Science, Google Scholar), institutional sources (MPOB publications, Indonesian Oil Palm Research Institute), and grey literature, including industry reports and government documents. The temporal scope prioritized publications from 2020 to 2026 to capture recent developments in maturity assessment technologies, updated economic data reflecting current market conditions, and contemporary policy frameworks, including revised ISPO and RSPO standards.

Search terms combined controlled vocabulary and natural-language queries, organized into thematic clusters. Primary terms included "oil palm," "Elaeis guineensis," "fresh fruit bunch," "FFB," "maturity," "ripeness," and "harvest timing." Secondary terms captured economic dimensions: "oil extraction rate," "OER," "economic loss," "yield gap," "quality premium," "free fatty acid," and "post-harvest loss." Boolean operators enabled the construction of comprehensive search strings such as ("oil palm" OR "Elaeis guineensis") AND ("fresh fruit bunch" OR "FFB") AND ("maturity" OR "ripeness") AND ("economic" OR "cost" OR "loss")

Inclusion criteria specified peer-reviewed journal articles, conference proceedings from recognized venues, and institutional publications from authoritative organizations (MPOB, IOPRI, RSPO). The geographic focus prioritized Indonesia and Malaysia as dominant producers, though relevant studies from other regions were included for comparative perspectives. Language criteria accepted English and Bahasa Indonesia publications, reflecting the dominant scientific communication channels in Southeast Asian palm oil research communities.

Literature Selection and Evaluation

Initial database searches yielded 847 potentially relevant documents, subjected to title and abstract screening against inclusion criteria. This process eliminated 612 documents due to insufficient relevance, methodological limitations, or violations of temporal criteria. Full-text assessment of the remaining 235 documents applied quality appraisal criteria evaluating methodological rigor, data quality, author credentials, and publication venue reputation. This yielded a core corpus of 94 high-quality sources forming the primary evidence base for synthesis.

Reference snowballing from included studies identified an additional 18 documents that met the criteria but were not captured in the initial searches, demonstrating the value of iterative search strategies. Particular attention was targeted to recent publications (2024-2026) to ensure the currency of economic data and market condition descriptions, given the rapid evolution of palm oil markets and policy environments.

Quality appraisal considered multiple dimensions: empirical studies were evaluated for sample representativeness, measurement validity, and analytical appropriateness; review papers were assessed for comprehensiveness and synthesis quality; industry reports were judged on data source transparency and potential bias. This multi-dimensional assessment enabled nuanced integration of diverse evidence types while maintaining a critical perspective on limitations.

Thematic Analysis

Data extraction employed structured templates to capture bibliographic information, study characteristics (design, location, sample), key findings related to the research questions, and direct quotations supporting the major themes. This structured approach facilitated systematic comparison across studies while preserving the contextual information necessary for interpretation [28].

Initial coding proceeded inductively, with line-by-line analysis of extracted findings generating descriptive codes capturing specific observations ("OER reduction in under-ripe FFB," "loose fruit collection efficiency," "DOBI values by maturity"). Iterative code refinement consolidated redundant codes and established hierarchical relationships, progressing from descriptive to interpretive coding. This process generated 127 initial codes, refined to 38 focused codes through consolidation.

Theme development involved grouping related codes into coherent analytical categories representing broader patterns across studies. Six primary themes emerged: (1) optimal maturity parameters and indicators, (2) economic impacts of under-ripe harvesting, (3) economic impacts of over-ripe harvesting, (4) post-harvest loss mechanisms, (5) determinants of non-optimal practices, and (6) intervention pathways for optimization. These themes structure the findings and discussion sections, with internal sub-themes providing granular organization.

Cross-study synthesis examined convergence and divergence in findings, identifying consistent patterns while noting methodological and contextual factors that explain discrepancies. For instance, reported OER values for under-ripe FFB ranged from 9.5% to 15%, with variations attributable to differences in maturity definitions, varietal characteristics, and processing conditions. Synthesis acknowledged these variations while identifying central-tendency estimates that represent the best available evidence.

Findings

Optimal Maturity Characteristics and Production Outcomes

Synthesis of agronomic and biochemical research provides convergent evidence for optimal FFB harvest timing at 23-24 weeks after anthesis, a window that coincides with peak oil accumulation and optimal alignment of quality parameters. Operational criteria for field implementation specify 5-10 loose fruits per bunch as reliable visual indicators, corresponding to internal mesocarp oil content exceeding 40% of fresh fruit mass. Color standards emphasize a predominantly reddish-orange outer fruit appearance, reflecting carotenoid accumulation patterns documented through spectroscopic analysis [29].

The oil extraction rate is the most economically consequential outcome variable, demonstrating strong sensitivity to maturity status. Under-ripe FFB consistently yields OER values in the 9.5-15% range across multiple studies, contrasting sharply with ripe FFB achieving 17-20% OER under equivalent processing conditions. The theoretical maximum OER of 20-23% reported for optimally processed ripe FFB establishes benchmarks for assessing harvest practice effectiveness. Notably, over-ripe FFB

demonstrates intermediate OER values (15-17%), suggesting that delayed harvesting imposes smaller quantitative penalties than premature harvesting, though quality dimensions tell a different story [30].

Quality parameter profiles exhibit systematic relationships with maturity status. DOBI values progress from 2.19 in under-ripe to 3.45 in ripe FFB, with practical implications for refining costs and market acceptance. Carotene content increases more than fourfold during the critical maturation window (175 mg/kg to 762 mg/kg), thereby affecting both nutritional value and oxidative stability. Chlorophyll retention in under-ripe fruits (5.38 mg/kg vs. near zero in ripe) results in green coloration in the extracted oil, requiring additional bleaching treatments and reducing commercial value [16].

Economic Implications of Under-ripe FFB Harvesting

Premature harvesting results in primary economic losses through direct OER reductions, with the magnitude depending on the severity of under-ripeness. The differential between severely under-ripe FFB (9.5% OER) and optimal material (20% OER) represents 52.5% yield reduction, translating to more than half of the potential oil production lost per ton of processed FFB. At typical FFB prices of 930 IDR/kg and CPO prices of 875-907 USD/tonne, these yield differentials generate substantial per-hectare revenue losses [31].

Malaysian national-scale estimates attribute RM 2.26 billion annual losses (approximately USD 538 million) to harvesting one under-ripe bunch per palm per cycle across the national planted area. While this represents a stylized calculation assuming uniform suboptimal practices, it illustrates the multiplicative effect of seemingly minor field-level deviations when aggregated across 5.7 million hectares. For individual smallholder households operating 2-5 hectare plots, premature harvesting of even 10-15% of bunches can reduce annual incomes by 5-8%, representing significant welfare implications in communities where palm oil provides primary cash income [32].

Quality-based price penalties compound quantitative losses. Under-ripe FFB receives lower grades in mill reception systems, with documented discounts of 300-500 IDR per ton compared to premium-grade ripe material. These pricing differentials reflect both lower actual oil yields and inferior quality characteristics (lower DOBI, higher chlorophyll) that increase mill processing costs and reduce final CPO market value. For smallholders selling through intermediaries rather than directly to mills, these quality signals may be attenuated, reducing economic incentives for maturity optimization [33].

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 5/14

Processing cost implications extend beyond purchase price differentials. Under-ripe FFB requires higher temperatures and longer processing times to achieve acceptable oil recovery, increasing energy consumption per ton of output. The higher chlorophyll content necessitates intensive bleaching, increasing refining costs by an estimated 5-8% compared to high-DOBI oil from ripe FFB. These downstream costs ultimately affect farmgate prices by influencing mills' willingness-to-pay calculations, imposing indirect economic penalties for premature harvesting [19].

Economic Implications of Over-ripe FFB Harvesting

Free fatty acid (FFA) formation is the primary quality-degradation mechanism in overripe FFB, with FFA content increasing at approximately 0.1% per 24 hours beyond optimal maturity. This hydrolytic lipid degradation stems from lipase enzyme activation in senescent fruit tissue, accelerated by elevated temperatures and mechanical damage from detached fruits. FFA levels exceeding 5% trigger quality grade downgrades and potential mill rejection, as high-FFA oil requires extensive neutralization treatments, increasing refining costs and reducing processed oil yields [34].

Loose fruit losses have a substantial economic impact on quantity, driven by delayed harvesting. Research across Malaysian estates quantifies loose fruit losses at 3-7% of total FFB production, with national aggregate estimates of RM 1.55 billion annually (USD 370 million) attributable to uncollected fruits. These losses reflect both fruit detachment in the field prior to harvest and continued detachment during transport and handling. Individual fruit oil content (6-8 grams per fruit for Tenera varieties) means that 20 uncollected fruits per bunch can reduce realized OER by 0.37-0.92%, depending on bunch size [35].

Collection efficiency for loose fruits demonstrates significant variability based on operational practices and terrain characteristics. Manual collection achieves rates of 200-250 kg per worker-day at costs of RM 120 per tonne, while mechanized collection systems (where terrain permits) reduce costs to RM 90.43 per tonne while improving recovery rates. However, many smallholder operations lack resources for systematic loose fruit collection, accepting these losses as unavoidable, despite their substantial aggregate economic impact [35].

Quality-based pricing penalties for over-ripe FFB can equal or exceed those for under-ripe material, despite intermediate OER values. Mills implement FFA-based discount schedules, with penalties increasing progressively above baseline thresholds (typically 3.5-4.5% FFA). For severely over-ripe material with FFA exceeding 5%, discounts can reach 15-20% of the base price,

reflecting both immediate processing cost increases and downstream market-value reductions. Farmers lacking timely market access may be forced to accept these discounts, particularly during peak production periods when mill capacity constraints create buyer's market conditions [10,11].

Post-Harvest Losses Across the Value Chain

Comprehensive assessment of post-harvest losses requires mapping multiple loss nodes from field harvest through mill processing. Indonesian plantation data reveal cumulative post-harvest losses of 5.21% of total production, disaggregated as follows: ground losses (1.73%), under-ripe FFB harvested but yielding suboptimal oil (0.51%), loose fruits lost at collection points (0.27%), and factory sorting rejections (2.70%). These percentages, while appearing modest individually, aggregate to substantial tonnages at scale operations, with each percentage point representing approximately 471,000 tonnes of lost FFB annually in Indonesia's 14.99 million-hectare planted area [36].

Ground losses encompass unharvested bunches, whether missed during harvest rounds or deemed uneconomical to collect due to access constraints. Malaysian estimates attribute RM 395 million annual losses (USD 94 million) to one unharvested bunch per palm per year, highlighting the economic significance of harvest completeness. For smallholders with limited labor availability, strategic decisions to prioritize accessible palms over difficult terrain or aged palms with lower productivity can systematically accumulate ground losses, particularly during peak production periods when labor constraints bind most severely [37].

Transport and handling losses occur between field collection and mill delivery, primarily due to mechanical damage, leading to fruit detachment and bruising that accelerate FFA formation. Studies document FFA increases of 0.5-1.5% during transport over poor infrastructure, with each hour of delay post-harvest contributing incrementally to quality degradation. The economic cost manifests through both direct FFA penalties and reduced overall oil recovery as damaged fruits leak oil or become contaminated. Indonesia's target of processing FFB within 24 hours of harvest reflects efforts to minimize these time-dependent losses, though achievement rates vary substantially across producer types [38].

Mill-level sorting and grading incur economic losses by rejecting substandard FFB or assigning it to lower-value processing streams. Quality grading systems implemented at mill reception assess visual maturity, FFA content, and contamination levels, with material failing standards subject to price discounts or rejection. The 2.70% factory sorting loss reported in Indonesian operations represents FFB that reached mills but failed quality standards, indicating either field-level assessment failures or economic desperation that forced the sale of known substandard

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 6/14

material. For mills, these rejections entail operational costs (grading labor, storage of rejected material) without corresponding revenue, creating incentives for stringent quality enforcement [36].

Economic Variability by Scale and Context

Smallholder and estate operations exhibit systematically distinct economic profiles in harvest optimization. Average smallholder FFB yields of 13.1 tonnes/ha/year contrast with estate yields exceeding 20 tonnes/ha/year, with harvest timing and post-harvest handling contributing substantially to these gaps. Independent smallholders performing 40% below good-practice benchmarks face particularly severe economic vulnerabilities, as lower absolute production volumes amplify per-unit costs and reduce bargaining power in FFB sales negotiations [39].

The MPOB reference pricing system, implemented in July 2020, aimed to enhance price transparency and quality-based compensation, with FFB prices calculated on a 1% OER basis. Under this framework, a 1% OER improvement translates directly to proportional price increases, theoretically creating strong incentives for maturity optimization. However, implementation challenges persist, particularly where smallholders sell through intermediaries (traders) rather than directly to mills. Traders may offer flat prices regardless of quality differences, thereby attenuating quality signals and reducing farmers' incentives to optimize. Research documents a 20% price premium for direct mill sales compared to trader purchases, suggesting substantial economic value in disintermediation, though many smallholders lack transportation or the volume scale for direct sales [40].

Regional variations in economic impacts reflect differences in terrain, infrastructure, market structures, and policy environments. Flat terrain operations in Indonesian Sumatra document annual losses of IDR 2.18 billion per estate (approximately USD 150,000 at 2024 exchange rates) from loose fruit losses alone, while hillier areas face higher labor costs for harvest and collection operations. Malaysian estates with better infrastructure achieve lower post-harvest losses but face higher labor costs, creating a different optimization calculus. CPO price volatility adds another dimension, with the USD 850-1,090/tonne range observed during 2024-2026 creating substantial variation in the absolute monetary value of percentage-based losses [41].

Participation in certification schemes (RSPO, ISPO) creates additional economic considerations. Certified producers access premium markets willing to pay 2-5% price premiums for sustainable palm oil, but certification standards impose requirements for harvest quality control and documentation that can increase operational costs. For smallholders, certification

represents an investment decision weighing premium access against compliance costs, with maturity optimization serving as one component of broader sustainability performance requirements [42].

Discussion and Analysis

Synthesis: Maturity Optimization as Economic Determinant

The evidence synthesis reveals that optimal FFB maturity is a critical determinant of economic performance, operating through multiple causal pathways simultaneously. The narrow optimal harvest window (23-24 WAA, 5-10 loose fruits) creates technical precision requirements that challenge conventional agricultural operations accustomed to wider tolerance ranges. This precision necessity stems from the non-linear, threshold-dependent relationships between maturity and economic outcomes—where small deviations from optimality result in disproportionate value losses through reduced OER and quality penalties [4].

The magnitude of documented economic impacts—billions of dollars annually at national scales—positions harvest optimization among the highest-value interventions available to the palm oil sector. Notably, achieving these gains requires neither genetic improvements, major capital investments, nor extensive land use changes, but rather enhanced management precision in existing operations. This low-cost, high-impact profile contrasts with many agricultural intensification pathways requiring substantial upfront investments, making maturity optimization particularly attractive from development policy perspectives [43].

The interaction between quality and quantity dimensions creates multiplicative rather than additive economic effects. A 50% OER reduction from premature harvesting (quantity impact) combined with 10-15% quality-based price discount (quality impact) generates approximately 55-57.5% total revenue loss per unit processed, not the 60-65% that simple addition would suggest, but still representing more than a halving of realized value. These compounding effects underscore the criticality of optimizing both dimensions simultaneously rather than managing them as independent objectives [19].

Mechanisms of Economic Loss: Multi-Level Analysis

At the biochemical level, economic losses arise from incomplete lipid biosynthesis in underripe fruits and enzymatic degradation in overripe material. Oil accumulation follows sigmoid kinetics controlled by coordinated expression of fatty acid synthase complexes and triacylglycerol assembly enzymes. Premature harvesting interrupts this biosynthetic program prior to completion, leaving mesocarp cells with incompletely filled oil bodies. Delayed harvesting initiates senescence programs, activating lipases that hydrolyze accumulated triglycerides into

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 7/14

free fatty acids and glycerol, degrading oil quality while maintaining quantity. These molecular mechanisms impose biological constraints on optimal timing, making understanding the process essential for intervention design [29].

Operational practices mediate biochemical potentials into realized economic outcomes. Labor management decisions—particularly harvest interval determination—directly influence maturity distributions in harvested FFB. Extended harvest intervals (e.g., 14-21 days vs. optimal 7-10 days) reduce labor costs per unit of FFB but systematically increase the proportion of overripe bunches and loose fruit losses. This creates economic trade-offs where short-term cost minimization undermines medium-term revenue maximization. It has been documented that shortening harvest intervals, while increasing immediate labor costs, generated net positive economic returns through improved fruit quality and reduced losses [21].

Implementing a grading system at collection points and mill gates provides quality control mechanisms but introduces additional operational complexities. On-site FFB grading enables immediate quality feedback to harvesters, creating learning loops that can improve maturity assessment skills over time. However, grading system effectiveness depends on assessment reliability—visual methods demonstrate substantial inter-observer variation (15-25% misclassification rates), while objective technologies (near-infrared spectroscopy, computer vision) offer greater consistency but require capital investments and technical capacity.publikasi [44-46].

Market and policy structures shape economic incentives for optimization. The MPOB 1% OER pricing framework theoretically aligns the interests of farmers and mills around maximizing quality. However, information asymmetries and transaction costs can distort these incentives. Smallholders often lack knowledge of their FFB's actual OER, making quality-based negotiations challenging. Traders acting as intermediaries may capture quality premiums without passing them on to producers, thereby breaking incentive linkages. Policy interventions addressing these market failures—through enhanced price transparency, facilitation of direct contracting, and trader licensing linked to fair pricing practices—represent institutional pathways for strengthening optimization incentives [34,47].

Determinants of Non-Optimal Harvesting Practices

Technical constraints in maturity assessment emerge as primary determinants of suboptimal practices. Visual assessment methods, while universally implemented due to their low cost and simplicity, exhibit inherent reliability limitations stemming from subjective judgment requirements and variability in external appearance. Color assessment shows particular challenges where fruit bunch exposure to sunlight varies based on canopy position, creating identical internal maturity states with divergent external appearances. Training programs can reduce, but not eliminate, these assessment errors, motivating the development of technology to detect objective maturity [14,48,49].

Economic pressures create competing incentives that sometimes favor non-optimal practices. Cash flow requirements may drive premature harvesting when household liquidity needs are acute, even when farmers understand the associated yield penalties. For smallholders facing income volatility and limited access to credit, immediate cash from selling available FFB—even at reduced prices—can take precedence over waiting for optimal maturity. Extended harvest intervals represent cost-reduction strategies when labor availability or affordability constraints bind, accepting increased loose fruit losses as an alternative to labor cost increases [21,50].

Information and knowledge barriers particularly affect smallholder operations with limited access to extension services. Many farmers lack a detailed understanding of the biochemical processes linking maturity to oil content, viewing harvest timing as a traditional practice rather than an optimizable management variable. Quality-based pricing mechanisms remain poorly understood in many producing communities, with farmers sometimes believing that all FFB receives uniform prices regardless of maturity or quality. This informational deficit undermines economic incentives for optimization even where price premiums theoretically exist [34].

Institutional factors, including labor market conditions, certification requirements, and policy environments, shape enabling conditions for optimization. Labor shortages in producing regions increase harvest interval length as a rationing mechanism, systematically pushing maturity distributions toward over-ripe status. RSPO and ISPO certification standards mandate harvest quality control documentation, creating compliance incentives for certified producers while leaving non-certified operations without external quality drivers. Government extension service capacity and prioritization determine smallholder access to training and technical support for improved practices [42,51].

Intervention Pathways for Optimization

Technological interventions offer pathways for enhancing maturity assessment accuracy and consistency. Computer vision systems employing deep learning algorithms (YOLOv4, YOLOv8) achieve>90% accuracy in ripeness classification from smartphone images, offering the potential for low-cost, field-deployable assessment tools. Raman spectroscopy provides laboratory-grade

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 8/14

precision based on carotene molecular signatures but requires equipment costs limiting scalability to large estates or mill reception points. Near-infrared (NIR) spectroscopy offers a cost-performance profile that is intermediate, suitable for mid-scale operations. Strategic technology deployment, matching tool characteristics to operational contexts and resource constraints, can progressively reduce assessment errors across the sector [52-54].

Managerial practice improvements require neither advanced technology nor substantial capital but depend on knowledge transfer and behavioral change. Optimal harvest interval management—maintaining 7-10 day cycles even during peak production periods—represents implementable practice change with immediate economic returns. Systematic loose fruit collection, whether manual or mechanized, converts losses into revenue at favorable cost-benefit ratios, with collection costs of RM 90-120/tonne substantially below market values. On-site FFB grading with immediate quality feedback creates learning systems that enhance harvester skills over time, generating cumulative quality improvements [55-57].

Quality-based incentive structures aligned with maturity optimization represent institutional interventions with potential for sector-wide impact. Transparent pricing that fully transmits quality premiums to producers—whether through direct contracts, certified trader programs, or cooperatives—strengthens economic motivations for optimization. Mills implementing differential pricing schedules that penalize substandard FFB while rewarding premium material creates market discipline, encouraging improved practices. For smallholders, participatory cooperative models that aggregate production volumes to enable direct mill sales while maintaining individual quality accountability show promise for combining scale economies with quality incentives [33,58].

Capacity-building programs targeting smallholder communities systematically address knowledge and information barriers. Extension services integrating maturity assessment training, education on the quality-price relationship, and harvest scheduling optimization can enhance management capabilities among large populations of small-scale producers. Demonstration plots illustrating the economic benefits of optimal practices provide concrete evidence that helps overcome skepticism about recommended changes. Farmer field schools, creating peer-learning environments, and leveraging social networks for knowledge diffusion while building community capacity for collective action to address shared challenges [10,11].

Implications for Industry Sustainability

Optimizing FFB maturity management offers substantial contributions to the sustainability of the palm oil industry across economic, social, and environmental dimensions. Economically, reducing the 5.21% post-harvest loss rate by even 50% through improved practices would generate billions of dollars in additional value without requiring land expansion, representing intensification pathways compatible with zero-deforestation commitments. The enhanced profitability from quality premiums strengthens producer economic resilience, particularly important for smallholders operating near subsistence margins [36,59].

Socially, quality-based pricing systems that implement fair compensation for superior FFB create inclusive value chain structures where smallholders can compete on quality rather than only on scale. This counters trends toward the consolidation and marginalization of small-scale producers, thereby maintaining the social fabric of palm-producing communities. The relatively low capital requirements for maturity optimization make it accessible to resource-constrained smallholders, in contrast to capital-intensive interventions that systematically favor larger operations [47,60].

Environmentally, yield intensification through harvest optimization reduces pressure to expand land to meet production targets. The documented potential to improve OER from current averages of 17-18% toward theoretical maximums of 22-23% represents approximately a 25% increase in production from existing planted areas. This intensification pathway aligns with sustainable palm oil commitments to increase production while stabilizing land footprints, addressing environmental concerns, and maintaining industry economic viability [61,62].

Climate adaptation considerations add urgency to optimization imperatives. Climate change impacts on oil palm include altered flowering phenology, changed fruit development rates, and increased pest/disease pressures—all potentially affecting optimal maturity timing and harvest scheduling. Building adaptive capacity through enhanced management precision and objective maturity monitoring systems positions the industry to respond to climate-driven changes while maintaining productivity and quality standards [63,64].

Conclusion

Substantive Conclusions

This qualitative literature review synthesizes compelling evidence establishing optimal FFB maturity as a critical determinant of economic outcomes in oil palm production systems. Operationally, optimal harvest timing centers on 23-24 weeks after anthesis, identifiable in field conditions by 5-10 loose fruits per bunch, reddish-orange fruit coloration, and biochemically

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 9/14

characterized by mesocarp oil content exceeding 40%, DOBI values above 3.0, and carotene concentrations exceeding 700 mg/kg.

The economic magnitude of non-optimal harvesting practices is substantial across all analytical scales. National-level estimates for Malaysia indicate annual losses approaching RM 4.2 billion (USD 1 billion), with Indonesia facing comparable impacts when losses from under-ripe harvesting, over-ripe harvesting, loose fruit losses, and post-harvest degradation are aggregated. At the estate level, documented losses of IDR 2.18 billion per operation per year represent significant portions of operating margins in an increasingly cost-competitive industry. For smallholder households, quality-based price differentials of 300-500 IDR/ton and OER variations from 9.5% to 20% between suboptimal and optimal practices translate to income variations of 15-30%, with direct welfare implications.

The pathways through which maturity deviations generate economic costs operate across multiple dimensions simultaneously. Under-ripe harvesting imposes primary costs through quantity reductions—OER declining from optimal 20-23% to 9.5-15%—representing approximately 50% yield loss per unit processed FFB. Secondary costs arise from quality degradation: low DOBI values (2.19 vs. 3.45), high chlorophyll content (5.38 mg/kg vs. near zero), and reduced carotene concentrations (175 vs. 762 mg/kg), which increase refining costs and reduce market value. Over-ripe harvesting triggers different loss mechanisms: FFA formation at 0.1% per 24 hours beyond optimal maturity, loose fruit losses of 3-7% of production, and quality penalties from enzymatic degradation. Post-harvest losses totaling 5.21% of production include field collection failures (1.73%), transport damage, and mill rejection (2.70%), with economic costs compounding throughout value chains.

Practical Recommendations

For farmers and plantation managers, evidence-based recommendations emphasize strict adherence to maturity criteria, with visual benchmarks of 5-10 loose fruits serving as practical field assessment tools pending broader adoption of objective technologies. Harvest interval optimization, maintaining 7-10 day cycles, even when labor costs increase, generates net positive economic returns through reduced over-ripe fractions and loose fruit losses, as documented by de Vos et al. (2023). Comprehensive loose fruit collection—whether manual or mechanized, based on scale and terrain—converts current 3-7% losses into revenue at favorable cost-benefit ratios where collection costs of RM 90-120/tonne substantially undervalue market prices. Rapid processing targets of <24 hours from harvest to milling minimize FFA formation and quality degradation, requiring coordination between field scheduling and mill delivery logistics.

For mills and processors, implementing transparent, quality-based pricing that fully reflects OER and quality parameter variations creates economic incentives that align with quality optimization objectives. The MPOB 1% OER pricing framework provides proven models, though effectiveness depends on the transmission of price signals to producers, particularly smallholders selling through intermediaries. On-site FFB grading at reception points enables immediate quality assessment and feedback, supporting both fair pricing and supplier development. Investment in objective maturity assessment technologies—NIR spectroscopy, computer vision systems, or Raman spectroscopy, depending on scale—reduces grading subjectivity while generating data for supplier performance tracking and incentive program design.

For policymakers and development organizations, recommendations emphasize multilevel interventions that address the technical, economic, and institutional determinants of practices. Strengthening extension services delivering integrated training in maturity assessment, quality-price relationships, and harvest scheduling builds smallholder capacity for optimization, with farmer field school models demonstrating effectiveness. Regulatory frameworks that ensure price transparency and fair, quality-based compensation protect smallholders from intermediary exploitation, with trader licensing systems linked to pricing practices compliance providing enforcement mechanisms. Support for technology transfer and adaptation makes objective maturity assessment tools accessible beyond large estates, with subsidy programs or cooperative purchasing models addressing capital constraints. Integration of quality management requirements into certification standards (ISPO, RSPO) creates external incentives for optimization while ensuring alignment with broader sustainability objectives.

Economic Cost Implications of Non-Compliance

Short-term economic costs of continued non-optimal practices manifest primarily through immediate production and quality losses. OER reductions of 40-50% from premature harvesting translate directly to equivalent revenue losses per hectare, devastating profitability in sectors where margins average 15-25% of gross revenue. Quality penalties of 300-500 IDR/ton compound these losses, and FFA-driven rejections create complete-loss scenarios in which FFB investment yields a zero return. Processing costs increase for substandard material—higher energy consumption for under-ripe FFB, and extensive neutralization and bleaching for high-FFA oil—reducing mill profitability and willingness to pay premium prices.

Long-term economic costs extend beyond immediate transactions to market access and competitive positioning. Premium market segments increasingly demand quality certifications and performance documentation, with sustainability-conscious buyers

willing to pay 2-5% premiums for verified high-quality sustainable palm oil. Producers unable to consistently meet quality standards face exclusion from these premium segments, limiting market opportunities to commodity channels with lower prices and greater volatility. Industry-reputation concerns arising from quality inconsistencies affect sector-wide market perceptions, with negative externalities when individual actors' poor practices harm collective industry interests.

Opportunity costs represent perhaps the largest economic implications of non-optimization. The differential between the current average OER of 17-18% and the achievable 22-23% from optimal practices represents approximately 25% foregone production from existing planted areas. Valorizing this gap at current CPO prices (USD 875-907/tonne) and typical yields (20-22 tonnes FFB/ha/year) generates opportunity costs of approximately USD 400-550 per hectare annually, aggregating to billions of dollars at national scales. For smallholders operating 2-5 hectare plots, these opportunity costs represent substantial portions of household incomes foregone through suboptimal management.

Future Research Directions

While this review synthesizes substantial evidence, important knowledge gaps remain. Longitudinal economic impact studies tracking producers who adopt optimization practices versus control groups would provide rigorous causal evidence on return-on-investment timelines and sustainability, strengthening business cases for practice change. Regional comparative analyses systematically examining how climate, soil, varietal, and institutional factors mediate optimal maturity parameters and economic impacts would enable context-specific recommendation refinement rather than universal prescriptions applied across diverse conditions.

Behavioral economics research investigating smallholder decision-making regarding harvest timing under conditions of uncertainty, liquidity constraints, and competing demands on limited labor would inform intervention design addressing actual decision contexts rather than idealized rational actor assumptions. Understanding why farmers sometimes harvest prematurely despite awareness of yield penalties requires examining complex trade-offs between immediate cash needs, risk perceptions, labor availability, and imperfect information that simple economic models overlook.

Methodological innovations in real-time maturity monitoring offer research frontiers with substantial practical applications. Integration of IoT sensor networks, satellite remote sensing for plantation-scale maturity mapping, and machine learning algorithms processing multi-source data could enable precision

harvest scheduling systems. Economic analysis of these technology adoption pathways—examining cost structures, scalability, and institutional requirements—would facilitate evidence-based investment decisions by producers, technology developers, and development finance institutions.

Climate change adaptation research investigating how shifting temperature and rainfall patterns affect oil palm phenology, fruit development rates, and optimal maturity timing will become increasingly critical. Understanding these climate-driven changes and developing adaptive management protocols preserves productivity and quality as environmental conditions evolve, representing essential research for long-term industry sustainability.

The palm oil industry stands at a critical juncture where economic, social, and environmental sustainability imperatives converge around production intensification without land expansion. Harvest maturity optimization represents a proven, accessible pathway toward this goal, offering substantial economic gains while supporting broader sustainability commitments. Realizing this potential requires coordinated action across multiple stakeholders—farmers improving management precision, mills implementing fair quality-based pricing, policymakers strengthening enabling institutions, and researchers continuing to refine understanding and develop tools. The evidence synthesized in this review demonstrates both the substantial costs of continued suboptimal practices and the equally substantial opportunities from systematic optimization, providing a compelling rationale for prioritizing harvest quality enhancement in palm oil sector development strategies.

References

1. Mike (2026) Palm Oil Price Guide: Global Market Analysis and Investment Insights. Grease Connections: Cooking Oil Recycling.

2. Judijanto L (2025) The Strategic Roles and Importance of Oil Palm Smallholders in Maintaining Sustainable Palm Oil Supply. ARACÊ 7(7): 40056-40079.

3. Judijanto L (2026) Navigating Uncertainy: Palm Oil Sector Outlook for 2026 through the Lens of Smallholder Welfare and Sustainability Imperatives. Rev Geopolítica 17(1): e1386.

4. Samian MR, Rizal AM (2024) Improving Palm Oil Productivity through Harvesting Practices," IJARBSS Int J Acad Res Bus Soc Sci 14(10): 2276-2284.

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 11/14

5. Md Yunos NSH, Chu CJ, Baharuddin AS, Mokhtar MN, Sulaiman A, et al. (2017) Enhanced oil recovery and lignocellulosic quality from oil palm biomass using combined pretreatment with compressed water and steam. J Clean Prod 142: 3834-3849.

6. Azahari DH (2019) Palm Oil Downstream Industry: Performance, Constraints, and Prospects. Forum Penelit. Agro Ekon 36(2).

7. CRIF (2025) Palm Oil Sector Strategy Amidst Price Decline Towards 2026. CRIF.

8. Judijanto L (2026) The Prospects and Challenges of Palm Oil Commodity Exchange Development in Indonesia. Acc Financ Manag J 11(1): 4053-4067.

9. IPOSS (2026) 2026 Palm Oil Outlook. Jakarta.

10. Marzukhi H, Mawar MY, Hameed LBM, Jamil MRM (2021) Smallholder Farmers in Malaysia's Oil Palm Industry: Issues and Challenges. J Manag Muamalah 11(2): 157-170.

11. Judijanto L (2025) Empowerment of Oil Palm Smallholders for Sustainable Palm Oil. Veredas do Direito 22(2): e3323.

12. Vos RED, Nurfalah L, Tenorio FA, Li LY, Monzon JP, et al. (2026) Shortening harvest interval, reaping benefits? A study on harvest practices in oil palm smallholder farming systems in Indonesia. Wageningen University & Research.

13. Ruswanto A, Amelan AH, Praseptiangga D, Partha IBB (2020) Effects of Ripening Level and Processing Delay on the Characteristics of Oil Palm Fruit Bunches. IJASEIT Int J Adv Sci Eng Inf Technol 10(1): 389-394.

14. Raj T, Hashim FH, Huddin AB, Hussain A, Ibrahim MF, et al. (2021) Classification of oil palm fresh fruit maturity based on carotene content from Raman spectra. Sci Rep 11(1): 18315.

15. Hasibuan HA (2020) Determination of Yield, Quality and Chemical Composition of Palm Oil and Palm Kernel Oil of Fresh Fruit Bunches with Variation Maturity as a Basic for Determining Harvest Maturity Standard. JPKS J Penelit Kelapa Sawit 28(3): pp. 123-132.

16. Tzuan GTH, Hashim FH, Raj T, Huddin AB, Sajab MS (2022) Oil Palm Fruits Ripeness Classification Based on the Characteristics of Protein, Lipid, Carotene, and Guanine/Cytosine from the Raman Spectra. Plants 11(15): 1936.

17. Tranbarger TJ, Dussert S, Joet T, Argout X, Summo M, et al. (2011) Regulatory Mechanisms Underlying Oil Palm Fruit Mesocarp Maturation, Ripening, and Functional Specialization in Lipid and Carotenoid Metabolism. Plant Physiol 156(2): 564-584.

18. Hudori M, Muhammad (2015) Quality Engineering of Crude Palm Oil (CPO): Using Multiple Linear Regression to Estimate Free Fatty Acid. Proc 8th Int Semin Ind Eng Manag 8(1): 26-33.

19. Tan BA, Nair A, Syawal MI, Low JYS, Kua SF, et al. (2023) Free Fatty Acid Formation Points in Palm Oil Processing and the Impact on Oil Quality. Agriculture 13(5): 957.

20. Woittiez LS (2019) On yield gaps and better management practices in Indonesian smallholder oil palm plantations. Wageningen University.

21. Nurfalah L, Tenorio FA, Li LY, Monzon JP, et al. (2023) Shortening harvest interval, reaping benefits? A study on harvest practices in oil palm smallholder farming systems in Indonesia. Agric Syst 211: 103753.

22. MPOB (2026) Notification on MPOB Daily Fresh Fruit Bunches (FFB) Reference Price at 1% OER. MPOB.

23. Zulkefli F, Othman N, Syahlan S, Zaini MR, Bakar MA (2017) Fresh Fruit Bunch Quality and Oil Losses in Milling Processes as Factors that Affect the Extraction Rate of Palm Oil. IJAFP Int J Agric For Plant 5: 99-104.

24. Hecker J, Kalpokas N (2026) The Guide to Literature Reviews. Atlas.ti Guides.

25. Snyder H (2024) Designing the literature review for a strong contribution. J Decis Syst 33(4): 551-558.

26. Qualtrics (2026) The ultimate guide to thematic analysis in qualitative research. Qualtrics: Articles and News.

27. Hecker J, Kalpokas N (2026) The Guide to Thematic Analysis. Atlas.ti Guides.

28. Thomas J, Harden A (2008) Methods for the thematic synthesis of qualitative research in systematic reviews. BMC Med Res Methodol 8(1): 45.

29. Sinambela R, Mandang T, Subrata IDM, Hermawan W (2020) A Ripeness Study of Oil Palm Fresh Fruit at the Bunch Different Positions. JTEP J Keteknikan Pertan 8(1): 9-14.

30. Ruswanto A, Ramelan AH, Praseptiangga D, Partha IBB (2020) Effects of Ripening Level and Processing Delay on the Characteristics of Oil Palm Fruit Bunches. Int J Adv Sci Eng Inf Technol 1: 391-396.

31. Varqa S (2025) Palm oil price forecast and production outlook 2026. Fastnarkets.

32. Alamsyah Z, Napitupulu D, Hamid E, Yanita M, Fauzia G (2021) Factors affecting the FFB price of independent smallholder oil palm farmers in Jambi Province. In IOP Conference Series: Earth and Environmental Science.

33. Witjaksono J et al. (2023) The assessment of fresh fruit bunches supply chain of palm oil independent smallholder farmers in southeast Sulawesi. Uncertain Supply Chain Manag 11(3): 941-950.

34. Judijanto L, Pamungkas DH (2024) Fair Pricing Formulation for Palm Oil Fresh Fruit Bunch Produced by Smallholder Farmers: A Development Method to Form a More Effective Formula for Palm Oil Fresh Fruit Bunch Pricing to Achieve a Fair Price for Smallhoder Farmers. J Lifestyle SDGs Rev 4: 1-28.

35. Rannando R, Tujannah M, Azmi Y, Sahfitra AA (2025) Economic Analysis of the Losses of Oil Palm (Elaeis guineensis Jacq.) Loose Fruits on Flat Terrain at Agritasari Prima Ltd. Open Sci Technol 5(1).

36. Pramana A, Hamzah A, Khoiri MA, Lada YG (2021) Palm Oil Fresh Fruit Bunch Loss and Post Harvest Risk Analysis at Koperasi Petani Sawit Mandiri (KOPSA-M) Pangkalan Baru, Siak Hulu, Kampar, Riau. JUATIKA J Agron Tanam Trop 3(2).

37. Abubakar MK, Kasim AS, Ishak MY, Uddin (2023) Maximizing oil palm yield: Innovative replanting strategies for sustainable productivity. J Environ Earth Sci 5(2): 1-12.

38. Shiddiq M, Hamzah Y, Nasir Z, Amanullah F, Rabin MF, et al. (2025) Physical properties of oil palm fresh fruit bunch varieties. Sci Technol Commun J 6(1): 23-32.

39. Judijanto L (2025) Légal Challenges and Opportunities in Promoting Sustainable Palm Oil Trade in Europe: A Review from a Social Economy Perspective. Sci Law 1: 144-150.

40. Sila A, Kirnadi AJ, Mursalin A (2025) Strategies for Developing Palm Oil Marketing Channels: A Literature Review on Profit Margins, Farmer Shares, and Distribution Chain Optimisation. INJOLE Int J Econ Lit 3(3).

41. Kondalamahanty A (2026) Palm oil prices to weaken in 2026, biofuel policy clarity crucial: survey. S&P Global: Agriculture, Energy Transitions, Biofuels, Oil Seeds, Renewables.

42. SPOS Indonesia (2022) The Comparison of ISPO and RSPO Certification to Achieve Sustainable Palm Oil Production in Indonesia.

43. Lim CH, Chea ZH, Lee XH, How BS, Ng WPQ, et al. (2021) Harvesting and evacuation route optimisation model for fresh fruit bunch in the oil palm plantation site. J Clean Prod 307: 127238.

44. Kurniawan R, Samsuryadi S, Mohamad FS, Wijaya HOL, Santoso B (2025) Advancing palm oil fruit ripeness classification using transfer learning in deep neural networks. Bull Electr Eng Informatics 14(2): 1126-1137.

45. Rosbi M, Khairuddin OU, Majeed APPA, Bakar SARSA (2024) Machine learning for automated oil palm fruit grading: The role of fuzzy C-means segmentation and textural features. Smart Agric Technol 9.

46. Septiarini A, Hatta HR, Hamdani H, Oktavia A, Kasim AA, et al. (2020) Maturity grading of oil palm fresh fruit bunches based on a machine learning approach. In 2020 5th International Conference on Informatics and Computing, ICIC.

47. Hasanah K, Muhaimin AW, Maulidah S (2024) Design of Supplier Selection of Fresh Fruit Bunches (FFB) of the Palm Oil Industry. J Penelit Pendidik IPA 10(11): 9129-9140.

48. Bonet I, Gongora M, Acevedo F, Ochoa I (2024) Deep Learning Model to Predict the Ripeness of Oil Palm Fruit. In Proceedings of the 16th International Conference on Agents and Artificial Intelligence, SCITEPRESS - Science and Technology Publications pp. 1068-1075.

49. Ashari S, Yanris GJ, Purnama I (2022) Oil Palm Fruit Ripeness Detection using Deep Learning," Sinkron 7(2): 649-656.

50. Woittiez LS, Wijk MTV, Slingerland M, Noordwijk MV, Giller KE (2017) Yield gaps in oil palm: A quantitative review of contributing factors. Eur J Agron 83: 57-77.

51. Judijanto L (2025) Governance Issues in Sustainability Certification: A Review of Implementation Challenges and Complexities. Int J Appl Res Sustain Sci 3(8): 701-718.

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 13/14

52. Nuraini LP, Rahardi M (2025) Detection of Ripeness in Oil Palm Fresh Fruit Bunches Using the YOLO12S Algorithm on Digital Images. J Appl Informatics Comput 9(4): 1633-1638.

53. Roman PC, Garcia JS, Dura E, Camba EAN, Calero JMA, et al. (2024) AI-based autonomous UAV swarm system for weed detection and treatment: Enhancing organic orange orchard efficiency with agriculture 5.0. Internet of Things 28: 101418.

54. Rosbi M, Omar Z (2025) Segmentation of Outdoor Oil Palm Fruit Images for Ripeness Detection using YOLO Algorithm and Features Thresholding," in AIP Conference Proceedings.

55. Shuib AR, Khalid MR, Bakri MAM (2018) Development of Oil Palm Loose Fruit Collecting Machine with Elevated Discharge Mechanism (Mark Iii). Int J Eng Res 7(10).

56. Hamid ZA, Chandiram SG, Fontaine RAH (2023) Knowledge Creation among Managers and Supervisors in Palm Oil Estates in Malaysia. Proc 24th Eur Conf Knowl Manag 24(1): 187-190.

57. Denashurya NI, Dolorosa NE, Kurniati D, Suswati D (2023) Overcoming Barriers to ISPO Certification: Analyzing the Drivers of Sustainable Agricultural Adoption among Farmers. Sustainability 15(23): 16507.

58. Renner S et al (2024) Smallholder RSPO certification, economic benefits and agrochemical use. Environ Res Lett 19(11): 114093.

59. Ningsih VY, Setiawan B, Asmara R, Andriani RD (2025) ISPO Certification and the Sustainable Development Goals: Readiness of Independent Smallholders in Indonesia (South Sumatra). Trans Chinese Soc Agric Mach 56(6): 37-55.

60. Judijanto L (2025) Exploring the Potentials of Artificial Intelligence and Digital Technologies in Transforming the Palm Oil Industry: A Review. J Information, Technol Policy 3(1): 1-13.

61. Gunawan WB (2025) Elucidating Indonesia's palm oil supply chain trends: A bibliometric approach. J Sustain Soc Eco-Welfare 3(1): 1-20.

62. Afifah HP, Nurliza N, Kurniati D (2021) Cooperatives as the Strengthening Effort for Oil Palm Replanting Program in Landak Regency. SOCA J Sos Ekon Pertan 15(1).

63. Rajakal JP, Tan RR, Andiappan V, Wan YK, Pang MM (2022) Data set on oil palm plantation production and LUC emissions under different management strategies. Data Br 43: 108329.

64. Judijanto L (2025) Who Pays for Climate Action? The Disproportionate Impact of Deforestation-Free Regulations on Smallholder Farmers. Eur J Manag Econ Bus 3(1): 3-13.

Citation: Judijanto L (2026) Economic Costs of Non-Optimal Oil Palm Fresh Fruit Bunch Harvesting: A Review on Maturity-Driven Production and Quality Implications. Shr J of Res & Sci 3.

Page 14/14