

Optimization of Palm Oil Processing Parameters to Improve Crude Palm Oil Yield and Energy Efficiency

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Abstract

Crude palm oil yield and mill energy consumption are conventionally managed as separate objectives, yet both are governed by the same set of controllable process parameters, so that improvements pursued independently frequently cancel one another. This paper reviews the parametric basis of palm oil milling and establishes where oil recovery and energy demand are coupled, where they are independent, and where a genuine trade-off exists. A structured review was conducted on peer-reviewed studies indexed in Scopus and SINTA published between 2010 and 2025, covering sterilization, threshing, digestion, pressing, clarification, and the mill utility system. Retained studies were coded for the unit operation examined, the parameters manipulated, the response measured, and the direction of the reported effect, and were then organised into a parameter-response matrix. The synthesis shows that sterilization is the dominant coupling point, since the same steam input that determines enzyme deactivation and bunch loosening also constitutes the largest single thermal load in the mill, while pressing and clarification affect oil recovery with comparatively little energy consequence. Evidence from mill-scale energy studies indicates that the milling process requires in the order of fifteen to twenty kilowatts and five hundred to seven hundred kilograms of steam per tonne of fresh fruit bunches, and that recovering vented sterilization steam and engine waste heat materially increases surplus power. The paper argues that parameter optimization should be formulated as a constrained multi-objective problem anchored on sterilization, and proposes a staged measurement protocol that mills can implement before committing capital to equipment change.

Keywords: crude palm oil yield; energy efficiency; process optimization

Introduction

A palm oil mill converts fresh fruit bunches into crude palm oil through a sequence of thermal and mechanical operations whose settings have been largely inherited rather than derived. Sterilizer cycle time and peak pressure, digester temperature and residence time, screw press cone pressure, and clarifier retention are typically fixed at values established when the mill was commissioned, and are adjusted reactively when oil losses rise or throughput falls. The consequence is that mills operate at parameter combinations that are feasible but rarely optimal.

Two performance measures dominate operational attention. The first is oil extraction rate, which determines revenue directly and which is eroded by oil retained in the empty bunches, the press cake fibre, the nut, and the mill effluent. The second is energy consumption, which the mill satisfies internally by burning fibre and shell and which therefore appears to be free. That appearance is misleading. Biomass consumed in the boiler is biomass unavailable for sale, for pelletisation, or for export power, and Umar et al. (2018) argued that treating mill residues as a costless fuel has systematically suppressed the development of higher-value biomass pathways.

The engineering literature has examined these two objectives largely in isolation. Studies of oil recovery focus on sterilization and pressing conditions and report yield or free fatty acid response. Studies of mill energy focus on the utility system and report boiler and turbine efficiency or surplus generation. Booneimsri et al. (2018), working with a forty-five tonne per hour mill, demonstrated that vented sterilization steam and biogas engine waste heat represent recoverable energy of substantial magnitude, and reported that the milling process consumes in the order of fifteen to twenty kilowatts and five hundred to seven hundred kilograms of steam per tonne of fresh fruit bunches. Saidur et al. (2010) established the general analytical framework for industrial boiler energy, exergy, and economic assessment on which such studies rest.

What has not been established clearly is the coupling structure between the two objectives. Because sterilization simultaneously determines enzyme deactivation, bunch loosening, mesocarp softening, and the largest thermal load in the mill, decisions taken to raise oil recovery propagate directly into energy demand and into the volume and strength of the effluent stream. Razman et al. (2022) documented the environmental consequences of that effluent stream, which is itself a function of upstream steam use. Without an explicit map of these couplings, mills optimise one objective while unknowingly degrading another.

This paper therefore reviews the parametric basis of palm oil milling with the specific objective of identifying where oil recovery and energy efficiency are coupled, where they are independent, and where a real trade-off must be resolved. The contribution is a parameter-response matrix that makes these relationships explicit, together with a staged measurement protocol that allows a mill to locate its own operating point before investing in equipment change. This matters because most Indonesian mills lack the instrumentation required to evaluate parameter changes, and capital is frequently committed on the basis of vendor claims rather than measured baselines.

Method

A structured literature review was conducted, appropriate to the objective of mapping relationships between process parameters and performance responses across unit operations that are studied by separate research communities.

Records were retrieved from Scopus and from SINTA-accredited national journals for the period 2010 to 2025. Search strings combined unit operation terms (“sterilization”, “digestion”, “screw press”, “clarification”, “palm oil mill”) with parameter terms (“temperature”, “pressure”, “residence time”, “optimization”) and response terms (“oil extraction rate”, “oil loss”, “free fatty acid”, “energy consumption”, “efficiency”). Inclusion required that a study manipulate at least one process parameter and report a measured response, or that it present a mill-scale energy analysis with a stated method.

Extraction recorded, for each study, the unit operation, the parameter varied and its range, the response measured, the direction and magnitude of the reported effect where stated, and the scale of the work, distinguishing laboratory, pilot, and mill-scale evidence. Scale was recorded explicitly because laboratory findings on oil release kinetics do not transfer directly to industrial sterilizers operating with bunch-scale heat transfer limitations.

Analysis proceeded by constructing a parameter-response matrix in which each parameter was assessed against both the oil recovery objective and the energy objective. A coupling was recorded where a single parameter produced a reported effect on both objectives; independence was recorded where an effect on one objective was reported with no plausible mechanism affecting the other; and a trade-off was recorded where the reported directions of effect opposed

one another. Because this study synthesises published evidence, no primary mill data were collected, and all quantitative values are attributed to their sources.

Result and Discussion

The parameter-response structure of the milling line

The reviewed evidence organises into a clear structure once parameters are assessed against both objectives simultaneously. Sterilization emerges as the dominant coupling point. Steam admitted to the sterilizer performs several functions at once: it deactivates the lipase activity responsible for free fatty acid formation, it loosens fruitlets from the stalk and thereby governs threshing efficiency, and it softens the mesocarp in preparation for digestion. Each of these functions improves with additional thermal input, while each additional unit of steam raises the mill's thermal load and increases oil absorption into the stalk and condensate.

Table 1. Process parameters and their relationship to the yield and energy objectives

No	Unit operation	Principal controllable parameters	Relationship between objectives
1.	Sterilization	Peak pressure, cycle duration, number of peaks, deaeration	Strongly coupled; the dominant trade-off point
2.	Threshing	Drum speed, feed rate, bunch condition	Largely independent; mechanical rather than thermal
3.	Digestion	Temperature, residence time, stirring arm condition	Weakly coupled through steam demand
4.	Pressing	Cone pressure, screw wear, feed consistency	Independent of thermal load; affects recovery only
5.	Clarification	Retention time, temperature, dilution ratio	Weakly coupled; affects effluent load strongly
6.	Utility system	Boiler excess air, steam pressure, condensate return	Energy objective only; no direct yield effect

The final column is the practically important one. Pressing and threshing offer oil recovery gains that carry no thermal penalty, which makes them the rational first target for any mill seeking improvement without capital investment. Boiler excess air control and condensate return deliver energy gains that carry no yield penalty. Only sterilization requires a genuine optimisation decision, because the parameter that raises recovery also raises energy demand and effluent strength.

Sterilization as the constrained optimisation problem

Framing sterilization as a constrained problem rather than as a search for a single optimum clarifies the decision. The mill must satisfy a quality constraint, since free fatty acid content above the trading specification renders the oil suitable only for non-food applications, and a throughput constraint, since sterilizer cycle time determines line capacity. Within those constraints the objective is to minimise total steam consumption per tonne of fresh fruit bunches. Formulated this way, additional steam beyond the point at which the quality constraint is satisfied represents pure loss, appearing simultaneously as fuel consumption, as oil absorbed into the empty bunches, and as increased condensate load.

Two upstream variables shift the entire response surface and are frequently overlooked in mill-level optimisation. The first is bunch ripeness at reception. Fruit that arrives over-ripe carries elevated free fatty acid before it enters the sterilizer, so no sterilization setting can recover the

quality lost in the field and during transport. The automated grading literature is directly relevant here: Suharjito et al. (2021) demonstrated ripeness classification on mobile devices using lightweight convolutional networks, and Suharjito et al. (2023) released annotated datasets collected from mill grading stations specifically to support this application. Abdullah et al. (2001) established the earlier colour-based discriminant approach on which this line of work builds. The second variable is the interval between harvest and processing, which governs the extent of enzymatic deterioration before any heat treatment is applied.

The implication is that sterilization optimisation is bounded by decisions made outside the mill gate. A mill that reduces cycle time without controlling reception quality will meet its energy target and fail its quality constraint. This is one reason why parameter optimisation studies conducted under controlled laboratory feedstock conditions frequently overstate the gains achievable in operating mills.

The energy side and the value of recovered heat

On the energy objective, the reviewed evidence indicates that the largest gains are available not from reducing process demand but from recovering energy that is currently discarded. Booneimsri et al. (2018) demonstrated for a forty-five tonne per hour mill that recovering vented sterilization steam, engine waste heat, and empty fruit bunch fuel raised surplus power to 2.834 megawatts with crude palm oil production and 4.223 megawatts without it, while extending cogeneration plant operation from an intermittent 4351 hours per year to 7500 hours. The associated carbon dioxide reduction was reported at 0.66 million tonnes.

These figures reframe the optimisation problem. If vented steam can be recovered, the marginal energy cost of an additional sterilization peak falls, which relaxes the trade-off identified above. Conversely, a mill without heat recovery faces the full penalty. The correct sequence is therefore to establish the recovery configuration first and to optimise sterilization parameters against the resulting energy cost structure, rather than the reverse. Saidur et al. (2010) provide the boiler-side analytical framework required to quantify that structure, and Cheah et al. (2023) and Siagian et al. (2024) situate the recovered biomass and heat within the wider set of alternative uses competing for the same streams.

A staged measurement protocol follows from this structure. In the first stage the mill establishes a baseline: oil losses measured separately in empty bunches, press fibre, nut, and final effluent, together with steam consumption per tonne of fresh fruit bunches and boiler efficiency. In the second stage the mill addresses the uncoupled parameters, namely press condition, threshing efficiency, boiler excess air, and condensate return, which yield improvement without requiring a trade-off decision. In the third stage the mill characterises its sterilization response surface under controlled reception quality. Only in the fourth stage should capital be committed to heat recovery or sterilizer replacement, since by then the mill possesses a measured baseline against which vendor performance claims can be evaluated.

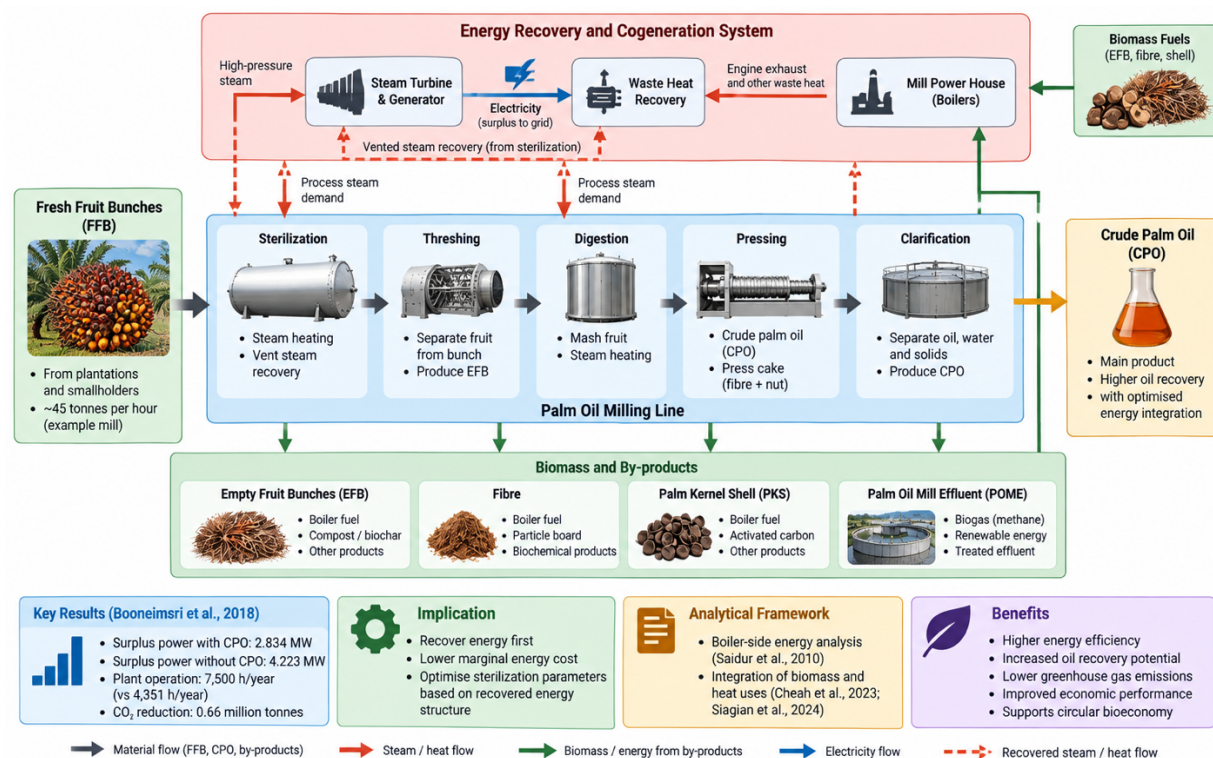


Figure 1. Coupling structure between oil recovery and energy demand across the milling line

Conclusion

This review set out to establish the parametric relationship between crude palm oil yield and mill energy efficiency. The evidence indicates that the two objectives are not uniformly opposed. Threshing and pressing improve recovery without thermal penalty, boiler and condensate management improve energy performance without yield penalty, and only sterilization presents a genuine trade-off, because the same steam input governs quality, loosening, thermal load, and oil absorption into the stalk simultaneously.

Two practical conclusions follow. First, sterilization optimisation should be formulated as a constrained minimisation of steam per tonne subject to a free fatty acid ceiling and a throughput floor, rather than as a search for maximum oil release. Second, the sequence of intervention matters: uncoupled improvements and heat recovery configuration should precede sterilization tuning, because heat recovery alters the marginal energy cost against which sterilization must be optimised. Further work should report mill-scale parameter trials in which oil losses and steam consumption are measured simultaneously, since the existing literature reports these responses in separate studies and the coupling must therefore be inferred rather than observed.

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