

Design and Performance Evaluation of an Automated Oil Palm Fruit Processing System for Improved Production Efficiency

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Abstract

Automation in palm oil processing has advanced most rapidly at the point where it is easiest to demonstrate, namely image-based fruit grading, while the mechanical and control subsystems that would allow a grading decision to change what the plant actually does remain largely undeveloped. This paper presents the design of an automated oil palm fruit processing system and a framework for evaluating its performance. The study followed a design research approach in which subsystem requirements were derived from published automation and grading work indexed in Scopus and SINTA, a system design was synthesised, and a performance evaluation framework was constructed and applied analytically. The proposed system comprises four subsystems: automated reception grading, batch identity tracking, adaptive sterilization control, and press and clarification monitoring, linked by a supervisory layer that carries grading information forward to downstream setpoints. The review of published grading work indicates that classification performance is now adequate for operational use, with reported accuracies in the region of eighty per cent for six-grade mobile classification and higher for coarser category schemes, and that annotated datasets collected from operating mill grading stations are publicly available. The evaluation framework proposed here specifies six measures spanning classification agreement, batch traceability, control response, oil recovery, energy consumption, and availability. The paper argues that automation value in this application arises from closing the loop between grading and process control rather than from grading accuracy alone.

Keywords: automation; oil palm fruit processing; performance evaluation

Introduction

Fruit arriving at a palm oil mill is graded at reception by human inspectors who assess colour, the presence of loose fruit, and visible damage. The grade determines the price paid to the supplier and, in principle, should determine how the fruit is processed. In practice it rarely does. Grading records are used for payment and are seldom carried forward to the sterilizer, so bunches of different maturity and different pre-processing history receive an identical thermal treatment.

This matters because maturity governs both the oil available for extraction and the free fatty acid already present when the fruit enters the plant. Under-ripe bunches release oil poorly and require more aggressive treatment; over-ripe bunches carry elevated acidity that no sterilization setting can reverse and that additional heat will worsen. A uniform treatment applied to a heterogeneous feed is therefore optimal for no part of it.

Automated grading has developed rapidly and is now technically capable of supporting a different arrangement. Abdullah et al. (2001) established colour-based discriminant grading using machine vision. Ibrahim et al. (2018) applied convolutional neural networks to ripeness

grading recognition. Suharjito et al. (2021) demonstrated classification on mobile devices using lightweight networks, reporting accuracy in the region of eighty per cent across six grades, and Suharjito et al. (2023) published annotated video and image datasets collected directly from mill grading stations with categories reflecting the conditions grading staff actually face. Rosbi et al. (2024) showed that fuzzy C-means segmentation combined with textural features achieves useful grading performance without the large datasets that deep learning requires, which matters for mills lacking the data to train a model from scratch.

The gap is not in classification. It is in what happens to the classification result. Published work reports accuracy against a labelled test set and stops there, leaving unaddressed the mechanical handling, batch identity, and control integration required for a grade to influence a sterilizer setpoint. Akhtar et al. (2023) observed a comparable pattern in plantation applications, where detection capability has outpaced operational integration, and Abubakar and Ishak (2024) concluded that the value of digital technologies in this sector depends on their integration with operational systems rather than on standalone capability.

This paper therefore presents a system design in which grading output is carried forward into process control, together with a framework for evaluating whether such a system performs. The contribution is twofold: a subsystem architecture that specifies the batch identity and control interfaces that published grading work omits, and an evaluation framework whose measures span classification, traceability, control, and process outcome rather than classification alone.

Method

The study followed a design research approach comprising requirement derivation, system synthesis, and construction of an evaluation framework. This approach is appropriate where the objective is to specify an artefact and the criteria by which it should later be judged.

Requirements were derived from published work retrieved from Scopus and from SINTA-accredited national journals for the period 2000 to 2025. Search strings combined automation terms (“automated grading”, “machine vision”, “deep learning”, “process control”, “automation”) with domain terms (“oil palm fruit”, “fresh fruit bunch”, “palm oil mill”). Each record was examined for the subsystem it addressed, the performance reported, and the interface it assumed with the rest of the plant. Assumed interfaces were recorded explicitly, since the unstated assumptions in grading studies proved to be the principal source of design requirements.

System synthesis assigned derived requirements to subsystems, with boundaries drawn where the engineering discipline and failure mode differed. A supervisory layer was specified to carry information across subsystem boundaries, since the central design problem identified during requirement derivation was the absence of any mechanism to propagate a grading result downstream.

The evaluation framework was constructed by identifying, for each subsystem, a measure that would reveal its failure, and by adding process-level measures that capture whether the system delivers its intended benefit rather than merely functioning. The framework was then applied analytically to the proposed design to identify which measures the design can currently satisfy and which require empirical determination. This is a design study: no physical system was constructed and no experimental performance data are reported. The evaluation framework is presented as a specification for subsequent implementation and testing, and all performance values cited are attributed to their original published sources.

Result and Discussion

Proposed system design

The proposed system comprises four subsystems linked by a supervisory layer. Reception grading acquires images of incoming bunches and classifies them. Batch identity tracking assigns an identifier at reception and maintains it through the sterilizer cage or conveyor into pressing. Adaptive sterilization control selects a cycle recipe according to the aggregate grade composition of the batch. Press and clarification monitoring measures the outcome and returns it to the supervisory layer, closing the loop.

Table 1. Subsystems of the proposed automated processing system

No	Subsystem	Function	Principal design requirement
1.	Reception grading	Image acquisition and ripeness classification of incoming bunches	Controlled illumination and fixed camera geometry
2.	Batch identity tracking	Assign and maintain a batch identifier through the process line	Physical batch separation compatible with plant layout
3.	Adaptive sterilization control	Select cycle recipe from batch grade composition	Recipe set validated against a free fatty acid ceiling
4.	Press and clarification monitoring	Measure oil losses and product condition per batch	Sampling frequency matched to batch residence time
5.	Supervisory layer	Propagate grade information to setpoints and record outcomes	Reconciliation with existing plant control system

The second subsystem is the one that published work consistently omits and it is the most demanding physically. A grading result is worthless unless the graded material can be identified later, which requires that batches remain separable through reception, tipping, and loading. Many mills operate a continuous tipping arrangement in which loads from different suppliers merge before the sterilizer, and in such a plant no grading system, however accurate, can influence downstream treatment without a layout change. This is a mechanical constraint on an ostensibly informational problem, and it should be assessed before any vision hardware is specified.

Grading performance and its operational sufficiency

The reviewed evidence indicates that classification is no longer the limiting factor. Suharjito et al. (2021) reported classification accuracy in the region of eighty per cent across six grades using a lightweight network suitable for mobile deployment, and noted that the choice among network architectures involves a trade-off between accuracy and inference speed. Suharjito et al. (2023) subsequently released annotated datasets comprising videos and images of bunch piles collected at operating mills, with categories corresponding to the conditions faced by mill grading sections rather than to idealised single-bunch imagery.

For the present application, coarse classification is sufficient. The sterilization recipe set proposed here distinguishes a small number of treatments, so the system does not require the fine grade discrimination that payment schedules demand. This is a favourable asymmetry: the accuracy adequate for process control is lower than the accuracy required for pricing, and the two applications can therefore be separated, with the automated system driving control while human grading continues to determine payment during any transition period.

Two qualifications apply. Rosbi et al. (2024) demonstrate that classical segmentation with textural features remains competitive where training data are limited, which is the situation of

most individual mills, and their approach is therefore the more realistic starting point for a plant without a large annotated dataset. Separately, any model must be revalidated under local illumination, camera geometry, and cultivar conditions, because performance reported on one dataset does not transfer unchanged. Savaş (2024) illustrates the ensemble approaches available where robustness across conditions is required.

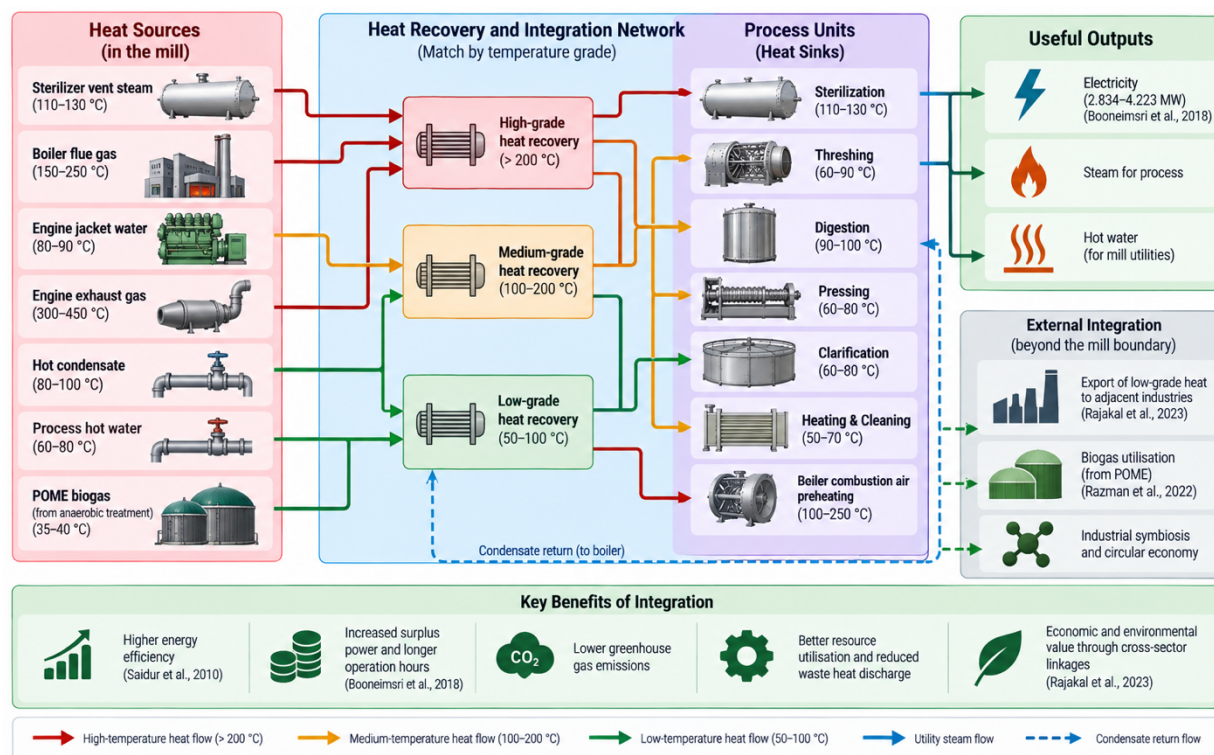


Figure 1. Architecture of the proposed automated oil palm fruit processing system

Performance evaluation framework

Evaluating this system by classification accuracy alone would measure the subsystem that is already adequate while ignoring the ones that determine whether the system delivers value. The framework proposed here therefore specifies six measures. Classification agreement compares automated grade against a human reference panel on the same material. Batch traceability records the proportion of processed tonnage for which a valid batch identity persists from reception to press. Control response measures whether the sterilizer actually executed the recipe selected. Oil recovery is measured as losses in empty bunches, press fibre, and nut, disaggregated by batch grade composition. Energy consumption is measured as steam per tonne of fresh fruit bunches, also disaggregated by grade composition. Availability records the proportion of operating hours during which the system functioned as intended.

The last three measures are the ones that matter for the investment case, and the fourth and fifth together determine whether the central hypothesis holds, namely that grade-adaptive treatment improves recovery, energy consumption, or both relative to uniform treatment. Booneimsri et al. (2018) provide the energy reference point against which the fifth measure should be interpreted, having established the steam and power requirement of the milling process per tonne of fresh fruit bunches, and Saidur et al. (2010) supply the boiler-side analytical basis for attributing steam consumption correctly.

Applying the framework analytically to the proposed design indicates that the first measure can be satisfied on the basis of published evidence, while the remaining five require empirical determination in an operating plant. This is the principal limitation of the present study: the design is derived from published subsystem evidence and has not been constructed, so the claimed benefit of grade-adaptive sterilization remains a hypothesis rather than a demonstrated result. The magnitude of that benefit is also likely to depend on the variability of the incoming feed, since a mill receiving consistently ripe fruit has little heterogeneity for an adaptive system to exploit.

Conclusion

This paper presented a design for an automated oil palm fruit processing system and a framework for evaluating it. The design comprises reception grading, batch identity tracking, adaptive sterilization control, and press and clarification monitoring, linked by a supervisory layer whose function is to carry grading information forward into process setpoints.

The central finding of the requirement analysis is that automated grading capability is already sufficient for this application, and that the limiting subsystem is batch identity tracking, which imposes a physical constraint on plant layout that informational solutions cannot circumvent. Mills operating continuous merged tipping cannot realise grade-adaptive processing without a layout change, and this should be assessed before vision hardware is specified. A second finding is that the accuracy required for process control is lower than that required for payment grading, which permits the two applications to be decoupled during implementation.

The proposed evaluation framework specifies six measures spanning classification, traceability, control response, oil recovery, energy consumption, and availability, of which only the first can be assessed from published evidence. Constructing the system and reporting these measures across a full season, with particular attention to whether grade-adaptive sterilization improves recovery and steam consumption relative to uniform treatment, is the necessary next step and would convert the present design proposition into a tested result.

References

- Abdullah, M. Z., Guan, L. C., & Mohd Azemi, B. M. N. (2001). Stepwise discriminant analysis for colour grading of oil palm using machine vision system. *Food and Bioproducts Processing*, 79(4), 223–231.
- Abubakar, A., & Ishak, M. Y. (2024). Exploring the intersection of digitalization and sustainability in oil palm production: Challenges, opportunities, and future research agenda. *Environmental Science and Pollution Research*, 31, 50036–50055. <https://doi.org/10.1007/s11356-024-34535-9>
- Akhtar, M. N., Ansari, E., Alhady, S. S. N., & Abu Bakar, E. (2023). Leveraging on advanced remote sensing- and artificial intelligence-based technologies to manage palm oil plantation for current global scenario: A review. *Agriculture*, 13(2), 504. <https://doi.org/10.3390/agriculture13020504>
- Booneimsri, P., Kubaha, K., & Chullabodhi, C. (2018). Increasing power generation with enhanced cogeneration using waste energy in palm oil mills. *Energy Science & Engineering*, 6(3), 154–173. <https://doi.org/10.1002/ese3.196>
- Fakhruddin, & Priyanto, W. (2024). Implementation of IoT-based optical sensors for real-time monitoring in palm oil processing. *Jurnal Inotera*, 9(2), 482–489.

- Ibrahim, Z., Sabri, N., & Isa, D. (2018). Palm oil fresh fruit bunch ripeness grading recognition using convolutional neural network. *Journal of Telecommunication, Electronic and Computer Engineering*, 10(3–2), 109–113.
- Mansour, M. A., Dambul, K. D., & Choo, K. Y. (2022). Object detection algorithms for ripeness classification of oil palm fresh fruit bunch. *International Journal of Technology*, 13, 1326.
- Rosbi, M., Omar, Z., Khairuddin, U., Majeed, A. P. P. A., & Bakar, S. A. R. S. A. (2024). Machine learning for automated oil palm fruit grading: The role of fuzzy C-means segmentation and textural features. *Smart Agricultural Technology*, 9, 100691.
- Saidur, R., Ahamed, J. U., & Masjuki, H. H. (2010). Energy, exergy and economic analysis of industrial boilers. *Energy Policy*, 38(5), 2188–2197. <https://doi.org/10.1016/j.enpol.2009.11.087>
- Savaş, S. (2024). Application of deep ensemble learning for palm disease detection in smart agriculture. *Heliyon*, 10(17), e37141. <https://doi.org/10.1016/j.heliyon.2024.e37141>
- Suharjito, Elwirehardja, G. N., & Prayoga, J. S. (2021). Oil palm fresh fruit bunch ripeness classification on mobile devices using deep learning approaches. *Computers and Electronics in Agriculture*, 188, 106359. <https://doi.org/10.1016/j.compag.2021.106359>
- Suharjito, Junior, F. A., Koeswandy, Y. P., Debi, Nurhayati, P. W., Asrol, M., & Marimin. (2023). Annotated datasets of oil palm fruit bunch piles for ripeness grading using deep learning. *Scientific Data*, 10, 72. <https://doi.org/10.1038/s41597-023-01958-x>