

Utilization of Oil Palm Empty Fruit Bunch Biomass for Renewable Energy Generation in Palm Oil Mills

Nur Hidayatul Hafizah^{1*}

¹ IPB University, Bogor, Indonesia

*Corresponding author: nur_hafidzah@apps.ipb.ac.id

Abstract

Empty fruit bunches are the largest solid residue leaving a palm oil mill and the only major residue stream that mills routinely fail to use as fuel, despite operating a boiler on site. This paper examines why that gap persists and what conversion route resolves it. A structured review was conducted on peer-reviewed studies indexed in Scopus and SINTA published between 2010 and 2025, covering direct combustion, torrefaction, pelletisation, gasification, and integrated mill energy systems using empty fruit bunch feedstock. Retained studies were coded for the conversion route, the fuel property addressed, the reported performance, and the scale of demonstration. The synthesis shows that the barrier to direct combustion is intrinsic to the raw material rather than to boiler design: high moisture content, low bulk density, heterogeneous particle size, and an alkali-rich ash that promotes slagging and fouling together make untreated empty fruit bunches a poor boiler fuel. Upgrading through torrefaction, densification, or hydrothermal treatment addresses these properties directly and produces a fuel comparable in handling terms to the shell and fibre already burned, while gasification offers a route to higher conversion efficiency at greater capital and operating complexity. Mill-scale energy analysis indicates that recovering empty fruit bunch fuel alongside vented sterilization steam and engine waste heat raises surplus power substantially. The paper concludes that the choice among routes is determined by whether the mill intends to consume the fuel internally or to sell it, and that this decision should precede technology selection.

Keywords: biomass energy; empty fruit bunch; palm oil mill

Introduction

Every palm oil mill operates a biomass boiler. Mesocarp fibre and palm kernel shell are fed to it continuously and, in most mills, supply the entire steam and electricity requirement of the process. Against that background the treatment of empty fruit bunches is anomalous. The bunches are generated in the same building, at the same time, in larger quantity than the shell, and yet they are trucked to the plantation for mulching, composted in windrows, or in some cases simply accumulated. A mill that runs a boiler declines to burn its largest solid residue.

The reason is a matter of fuel properties rather than of policy. Empty fruit bunches leave the thresher saturated with condensate and press liquor, are physically bulky and irregular, and carry an ash rich in potassium and chlorine. Hardianto et al. (2023) reviewed upgrading processes for empty fruit bunches as an alternative solid fuel and set out the case systematically: the raw material is deficient in exactly the properties that a boiler fuel requires, and each deficiency has a corresponding treatment.

Interest in resolving this has intensified because the alternative uses of mill biomass have become more valuable. Umar et al. (2018) argued that a policy framework and industry roadmap are prerequisites for sustainable oil palm biomass electricity generation, since individual mills

face investment thresholds they cannot cross unaided. Cheah et al. (2023) and Siagian et al. (2024) situate empty fruit bunch energy within a wider circular bioeconomy in which the same feedstock is contested by soil amendment, materials, and chemical pathways. Anyaoha et al. (2018) evaluated the soil ameliorant route specifically and established that it delivers measurable agronomic value, which means that energy use must justify itself against a real alternative rather than against disposal.

The literature on conversion technology is extensive but organised by process rather than by decision. Studies report torrefaction conditions and resulting fuel properties, or gasification performance under specified conditions, without addressing the prior question of what the mill intends the fuel to do. That question is decisive, because a fuel destined for the mill's own boiler faces a different specification from one destined for sale to a coal-fired power station or an export pellet market.

This paper therefore reviews empty fruit bunch energy conversion with the objective of relating each route to the deployment decision it serves. The contribution is to organise the technical evidence around the mill's actual choice, namely whether to consume or to sell, and to identify which fuel properties become binding under each option. This reframing matters because mills currently evaluate technologies against generic performance claims rather than against the specification their own intended use imposes.

Method

A structured review was conducted on published evidence concerning the conversion of oil palm empty fruit bunches into energy carriers suitable for use in or export from palm oil mills.

Records were retrieved from Scopus and from SINTA-accredited national journals for the period 2010 to 2025. Search strings combined feedstock terms ("empty fruit bunch", "OPEFB", "oil palm biomass") with conversion terms ("combustion", "co-firing", "torrefaction", "pelletisation", "gasification", "hydrothermal carbonisation") and application terms ("boiler", "power generation", "palm oil mill", "solid fuel"). Inclusion required that a study report fuel property characterisation, conversion performance, or a mill-scale energy analysis with a stated method.

Extraction recorded the conversion route, the process conditions applied, the fuel properties measured, the reported performance, the demonstration scale, and any limitation identified by the authors. Fuel properties were recorded under a common set of headings comprising moisture, calorific value, bulk and energy density, ash content and composition, and grindability, so that routes could be compared on a consistent basis despite differing reporting conventions.

Analysis proceeded in two steps. First, the deficiencies of untreated empty fruit bunches as a boiler fuel were established and each was matched to the treatments reported to address it. Second, each conversion route was assessed against two deployment cases, internal consumption and external sale, on the reasoning that these impose different binding specifications. As this study synthesises published evidence, no experimental work was conducted and all reported values are attributed to their original sources.

Result and Discussion

Why untreated empty fruit bunches perform poorly as boiler fuel

Four properties account for the observed reluctance to burn raw material. Moisture content on discharge from the thresher is high, so that a substantial fraction of the fuel's calorific value is consumed evaporating water rather than raising steam. Bulk density is low and particle size

heterogeneous, which complicates conveying, feeding, and combustion control. Ash content is elevated relative to shell. Most consequentially, the ash is rich in potassium and chlorine, a composition associated with low ash fusion temperature, slagging on furnace surfaces, and fouling of superheater tubes.

Hardianto et al. (2023) reviewed the upgrading responses to these deficiencies, covering torrefaction, densification, and hydrothermal treatment, and set out how each modifies the property profile. Rusdianasari et al. (2023) characterised empty fruit bunches specifically as a co-firing feedstock, which is the application in which ash behaviour matters most because the material must be compatible with a furnace designed for coal.

Table 1. Conversion routes and the fuel deficiencies each addresses

No	Conversion route	Deficiency principally addressed	Representative evidence
1.	Drying and direct combustion	Moisture only; density and ash unchanged	Booneimsri et al. (2018)
2.	Densification (pelletisation)	Bulk density, particle uniformity, handling	Hardianto et al. (2023)
3.	Torrefaction	Moisture, energy density, grindability, hygroscopicity	Hardianto et al. (2023)
4.	Co-firing with coal	Dilutes ash-related risk within an existing furnace	Rusdianasari et al. (2023)
5.	Gasification	Converts solid to gaseous fuel for higher-efficiency conversion	Al-Muraisy et al. (2025)
6.	Slow pyrolysis to char	Produces a dense carbon product for fuel or soil use	Mohd Bakhtiar et al. (2019); Hadi & Norazlina (2021)

The table makes clear that no single treatment resolves every deficiency. Drying addresses moisture but leaves the material bulky and the ash unchanged. Densification improves handling but does not alter ash chemistry. Torrefaction improves several properties simultaneously and is consequently the most discussed route, but it consumes energy and reduces mass yield. Gasification changes the conversion pathway entirely and, as Al-Muraisy et al. (2025) demonstrate in the context of solar-driven carbon dioxide gasification producing syngas and biochar, opens co-product options that combustion does not.

The consume-or-sell decision

The deployment intention determines which properties bind. Where the mill intends to consume the fuel internally, transport and storage are short, and hygroscopicity and bulk density therefore matter less. What binds instead is ash behaviour in the mill's own boiler, since slagging imposes cleaning downtime that a mill operating during a peak crop season can ill afford. The rational route in this case is drying combined with controlled co-firing ratios against fibre and shell, keeping the alkali loading within the tolerance of the installed furnace.

Where the mill intends to sell the fuel, the binding constraints invert. Buyers specify calorific value, moisture, and ash on delivery; the material must survive storage and transport without reabsorbing moisture or degrading; and bulk density governs freight cost per unit of delivered energy. Torrefaction and densification address precisely these constraints, and the additional processing cost is recovered through the price premium a specification-compliant fuel commands. Hardianto et al. (2023) frame the upgrading literature in these terms.

This distinction explains an otherwise puzzling feature of the field. Studies optimising torrefaction conditions for maximum energy density are addressing the export case, while mills evaluating those results for internal use frequently conclude that the process is not worth its cost, because the properties being optimised are not the properties that constrain them. Both parties are correct within their own deployment case.

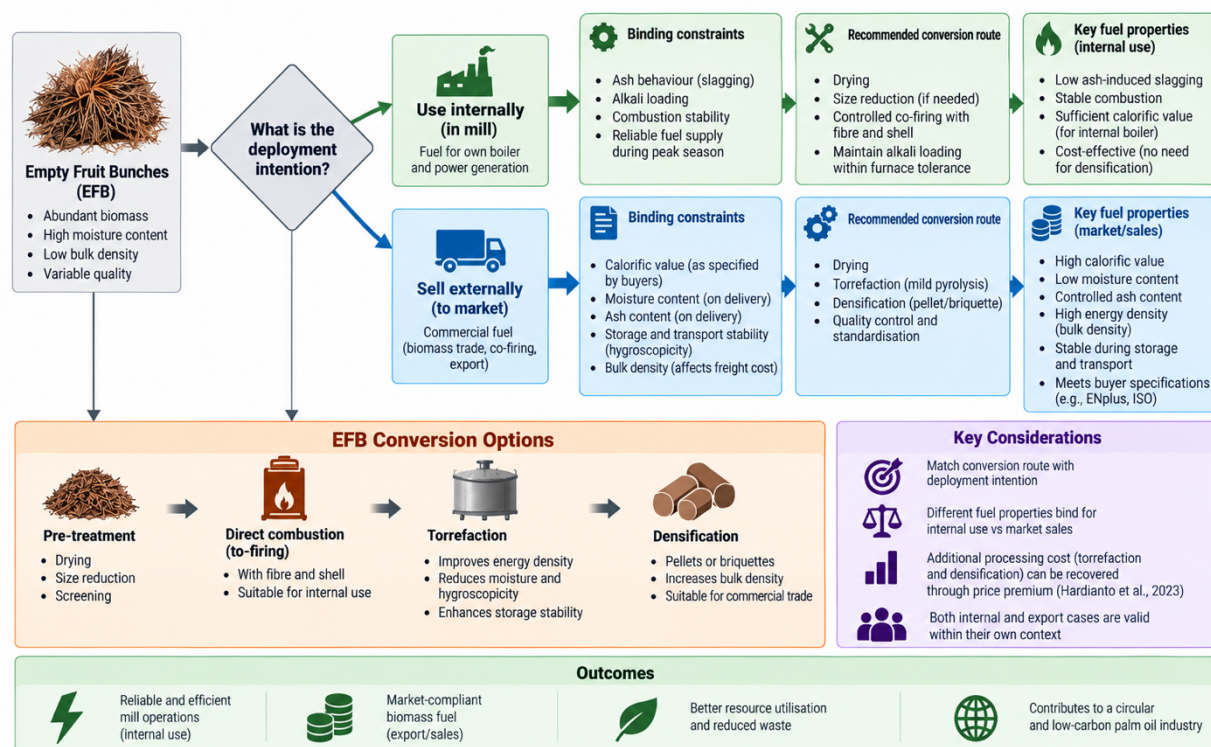


Figure 1. Decision structure for empty fruit bunch energy conversion in a palm oil mill

Integration with the mill energy system

Empty fruit bunch fuel does not enter an empty energy system. The mill already generates steam and electricity from fibre and shell, and in many cases also operates a biogas facility on mill effluent. The relevant question is therefore the marginal contribution of empty fruit bunch fuel to an existing configuration rather than its standalone performance.

Booneimsri et al. (2018) address this directly. For a forty-five tonne per hour mill they modelled the recovery of vented sterilization steam, engine waste heat, and empty fruit bunch biomass fuel within an enhanced cogeneration scheme, reporting surplus power of 2.834 megawatts with crude palm oil production and 4.223 megawatts without, an extension of cogeneration operation from an intermittent 4351 hours per year to 7500 hours, and an associated carbon dioxide reduction of 0.66 million tonnes. The extension of operating hours is the more consequential result for export viability, because an intermittent generator cannot support a firm power contract regardless of its rated capacity.

Two constraints qualify this conclusion. First, the alternative uses of the feedstock are not negligible. Anyaoha et al. (2018) established the agronomic value of the soil ameliorant route, and a mill that diverts all empty fruit bunches to fuel forgoes the nutrient return and organic matter contribution that the plantation would otherwise receive, which appears later as increased fertiliser demand. Second, Umar et al. (2018) note that export power depends on grid access and

tariff arrangements that lie outside the mill's control, so a technically sound configuration may remain commercially unviable. Cheah et al. (2023) and Siagian et al. (2024) place both constraints within the broader competition for palm biomass.

Conclusion

This review examined why palm oil mills, which already operate biomass boilers, generally do not burn their largest solid residue, and what conversion route resolves the problem. The evidence indicates that the obstacle is intrinsic to the raw material: high moisture, low bulk density, heterogeneous particle size, and alkali-rich ash together make untreated empty fruit bunches a poor boiler fuel, and each deficiency has a corresponding but partial treatment.

The principal conclusion is that route selection follows from the deployment decision rather than from technical performance in the abstract. Internal consumption is constrained by ash behaviour in the installed boiler and is best served by drying with controlled co-firing ratios; external sale is constrained by delivered specification, storage stability, and freight density and is best served by torrefaction with densification. Mill-scale evidence confirms that empty fruit bunch fuel makes a material contribution to surplus power when recovered alongside vented steam and engine waste heat, with the extension of continuous operating hours being more important for export viability than rated capacity. Mills should therefore settle the consume-or-sell question, and confirm grid access where sale is intended, before selecting conversion technology. Further work reporting ash deposition behaviour in operating mill boilers under defined empty fruit bunch co-firing ratios would address the most significant remaining evidence gap.

References

- Al-Muraisy, S. A. A., Chuayboon, S., Soares, L. A., Buijnsters, J. G., Ismail, S., Abanades, S., van Lier, J. B., & Lindeboom, R. E. F. (2025). Carbon capture through solar-driven CO₂ gasification of oil palm empty fruit bunch to produce syngas and biochar. *Energy*, 323, 135805. <https://doi.org/10.1016/j.energy.2025.135805>
- Anyaocha, K. E., Sakrabani, R., Patchigolla, K., & Mouazen, A. M. (2018). Critical evaluation of oil palm fresh fruit bunch solid wastes as soil amendments: Prospects and challenges. *Resources, Conservation and Recycling*, 136, 399–409. <https://doi.org/10.1016/j.resconrec.2018.04.022>
- 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>
- Cheah, W. Y., Siti-Dina, R. P., Leng, S. T. K., Er, A. C., & Show, P. L. (2023). Circular bioeconomy in palm oil industry: Current practices and future perspectives. *Environmental Technology & Innovation*, 30, 103050. <https://doi.org/10.1016/j.eti.2023.103050>
- Hadi, A. R. A., & Norazlina, A. S. (2021). The effects of pyrolysis temperature on chemical properties of empty fruit bunch and palm kernel shell biochars. *IOP Conference Series: Earth and Environmental Science*, 757(1), 012029. <https://doi.org/10.1088/1755-1315/757/1/012029>
- Hardianto, T., Wenas, A. A., & Juangsa, F. B. (2023). Upgrading process of palm empty fruit bunches as alternative solid fuel: A review. *Clean Energy*, 7(6), 1173–1188. <https://doi.org/10.1093/ce/zkad059>

- Harahap, F., Leduc, S., Mesfun, S., Khatiwada, D., Kraxner, F., & Silveira, S. (2019). Opportunities to optimize the palm oil supply chain in Sumatra, Indonesia. *Energies*, 12(3), 420. <https://doi.org/10.3390/en12030420>
- Mohd Bakhtiar, M. H. A., Abu Sari, N., Yaacob, A., Yunus, M. F., & Ismail, K. (2019). Characterization of oil palm empty fruit bunch (EFB) biochar activated with potassium hydroxide under different pyrolysis temperature. *Journal of Engineering Science and Technology*, 14(5), 2792–2807.
- Rusdianasari, Arisetyadhi, I., Kalsum, L., Bow, Y., Syarif, A., & Arifin, F. (2023). Characterization of empty fruit bunch of palm oil as co-firing biomass feedstock. *Asian Journal of Applied Research for Community Development and Empowerment*, 7(1), 74–78. <https://doi.org/10.29165/ajarcde.v7i1.237>
- Siagian, U. W. R., Wenten, I. G., & Khoiruddin, K. (2024). Circular economy approaches in the palm oil industry: Enhancing profitability through waste reduction and product diversification. *Journal of Engineering and Technological Sciences*, 56(1), 25–49. <https://doi.org/10.5614/j.eng.technol.sci.2023.56.1.3>
- Umar, M. S., Urmee, T., & Jennings, P. (2018). A policy framework and industry roadmap model for sustainable oil palm biomass electricity generation in Malaysia. *Renewable Energy*, 128, 275–284. <https://doi.org/10.1016/j.renene.2017.12.060>