

Basic Properties of Oil Palm Empty Fruit Bunch (EFB): Dry Solids, Moisture, and a Comparative Review of Compositional, Proximate, Ultimate, Calorific and Inorganic Data

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Article 1 of a series on the characterisation and valorisation of oil palm empty fruit bunch

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Abstract

The palm oil industry of South-East Asia generates very large volumes of oil palm empty fruit bunch (EFB), a fibrous lignocellulosic residue that remains after the oil-bearing fruitlets are stripped from the fresh fruit bunch. EFB is most often discarded in the plantation, where it decomposes and represents both an environmental liability and an unexploited resource. The recovery, conversion or valorisation of EFB - whether as solid fuel, as a substrate for anaerobic digestion, or as a feedstock for sugar and bio-product recovery - depends first on knowing its basic physical and chemical properties. This article, the first of a series, reports a field measurement of the two properties most relevant to any handling or conversion decision: dry solids (DS) and moisture content. A 1 kg sample of fresh EFB collected at a working mill in West Kalimantan, Indonesia, was oven-dried at 105 C. The dry solids content was 56.08 % and the moisture content 43.92 %, with a propagated measurement uncertainty of approximately ± 0.01 % ($k = 2$) arising from balance readability. We argue that the dominant real-world uncertainty in any single EFB property is not instrumental but biological - feedstock heterogeneity and sampling - and we frame our result accordingly. The measured value is then compared with the literature, and a summary of EFB biochemical composition, proximate analysis, ultimate analysis, calorific value and inorganic (ash) chemistry is compiled from published sources to provide a reference baseline for the remainder of the series.

1. Introduction

Oil palm empty fruit bunch is a by-product of the palm oil milling process. Fresh fruit bunches (FFB) are harvested from the African oil palm, *Elaeis guineensis*, and transported to a palm oil mill where the oil is extracted. During extraction the FFB is sterilised under steam pressure - typically in the region of 130-143 C for around 45 minutes - after which the fruitlets are threshed from the bunch and the palm oil is recovered from the fruitlets by screw press. The bunch that remains, stripped of its fruitlets, is the empty fruit bunch and is discarded as waste.

An industry-standard 60 tonne-per-hour mill receives roughly 900-1000 tonnes of FFB per day. The EFB fraction is approximately 23-25 % of FFB by weight, so such a mill produces in the order of 190-230 tonnes of moist EFB per day, or an annualised average of around 66,000 tonnes. The great majority of mills dispose of this material by trucking it to nearby plantation areas and dumping it in piles or windrows, where it is left to decompose. A small number of mills press the EFB to recover residual oil, and a very small number compost a portion of it. Because EFB is treated as a waste that costs money to remove, it is frequently managed poorly.

Whatever the chosen end-use - combustion for steam and power, anaerobic digestion to biogas, mulching, composting, or hydrolysis to fermentable sugars - the engineering and economics begin with the feedstock's basic properties. Moisture governs transport cost, storage stability, combustion efficiency and digester loading; biochemical composition governs sugar and biogas potential; calorific value governs fuel value; and the inorganic (ash) chemistry, in particular potassium and chlorine, governs slagging, fouling and corrosion in thermal conversion. This article establishes those baseline properties: it reports our own dry-solids and moisture measurement and compiles the published values for the wider property set.

2. Physical Description of EFB

An oil palm empty fruit bunch is a fibrous mass consisting of an inner core (pith) and outer spikelets or frondlets. An individual bunch weighs around 1-2 kg and is approximately 30 cm long. The frondlets are comparatively oily, while the pith is highly fibrous. The frondlets are easily separated from the pith by cutting, and once the fibre is cut the individual fibres tend to separate from the mass. Fibre cut to lengths not exceeding about 1 cm is considerably easier to disperse in water at working solids loadings than fibre in the 3-5 cm range. Following a hot-water oil-removal step the material is similar in appearance and texture to fibrous coconut coir.



Figure 1. Prepared EFB fibre. The frondlets have been cut from the bunch and reduced to short lengths, at which point the individual fibres separate readily, giving the coir-like texture described in the text.

As-received EFB is therefore a heterogeneous, anisotropic, high-moisture biomass. Its properties vary with the position in the bunch (frondlet versus pith), with the age and handling of the material, and with whether it has been pressed or drained. This heterogeneity is central to the interpretation of any single measured property, as discussed below.

3. Materials and Methods

3.1 Sample collection

Fresh oil palm empty fruit bunches were collected directly from the Sei Kerandi Mill, West Kalimantan, Indonesia. Obtaining fresh samples directly from the mill is important because this is the actual

feedstock for any downstream process. Field-scale samples of at least 1 kg were used in preference to the ~50 g samples typical of bench studies, both to better represent the heterogeneity of the bulk material and to preserve sufficient significant figures when scaling mass balances by a factor of a thousand from kilograms to tonnes.

3.2 Sample preparation

Using hand shears the frondlets were cut from the coir-like pith and then cut into approximately 1 cm lengths, at which length the individual fibres separated readily. Sufficient fibre was prepared to give a sample mass of approximately 1 kg.

3.3 Dry solids determination

The dry solids content was determined gravimetrically by oven drying. The initial (wet) mass of the prepared sample was recorded. The sample was placed in an oven at 105 C and dried in successive sessions (2 h + 2 h + 2 h), being weighed after each session until the mass was constant, giving a total drying time of 6 hours. Dry solids and moisture were calculated from the initial wet mass and the final constant (dry) mass:

$$DS (\%) = (m_{\text{dry}} / m_{\text{wet}}) \times 100 \quad \text{Moisture} (\%) = 100 - DS$$

All weighings were made on a balance with a readability of 0.1 g. The standard uncertainty of each weighing was taken as a rectangular distribution of half-width equal to the readability, $u(m) = 0.1 / \sqrt{3}$ g = 0.058 g. The combined standard uncertainty of the dry-solids ratio was propagated as $u(DS)/DS = \sqrt{[(u(m_{\text{dry}})/m_{\text{dry}})^2 + (u(m_{\text{wet}})/m_{\text{wet}})^2]}$.

4. Results: Dry Solids and Moisture

For the sample measured (Sample 1), the initial wet mass was 1007.8 g and the final dry mass after 6 hours at 105 C was 565.2 g, a loss of 442.6 g of water. This gives:

Quantity	Value	Std. uncertainty	Expanded (k=2)
Wet mass, m_{wet}	1007.8 g	0.058 g	0.12 g
Dry mass, m_{dry}	565.2 g	0.058 g	0.12 g
Water removed	442.6 g	0.082 g	0.16 g
Dry solids, DS	56.08 %	0.007 %	0.01 %
Moisture	43.92 %	0.007 %	0.01 %

Table 1. Dry solids and moisture of Sample 1 with propagated measurement (balance) uncertainty.

The dry solids content of the sample is therefore **56.08 % +/- 0.01 %** and the moisture content **43.92 % +/- 0.01 %** (expanded uncertainty, $k = 2$), where the stated uncertainty reflects balance readability only.

4.1 On the meaning of the uncertainty

The propagated balance uncertainty of +/- 0.01 % is, by itself, misleadingly small, and it would be poor practice to report it as the uncertainty of "the moisture content of EFB." It is only the uncertainty of this one mass ratio for this one prepared sample. The dominant uncertainty in any statement about EFB

moisture is not instrumental but arises from two other sources: the **biological heterogeneity** of the material (frondlet versus pith, bunch-to-bunch and mill-to-mill variation, age and degree of draining) and the **sampling** procedure used to obtain the 1 kg test portion from a far larger and non-uniform bulk. These contributions cannot be quantified from a single sample. A defensible figure for the moisture of a given EFB stream therefore requires replicate sampling and drying (for example $n \geq 3$, following the spirit of the ASTM and NREL biomass procedures), from which a sample standard deviation can be computed. The balance contribution derived here would then be a negligible term added in quadrature to that much larger sampling standard deviation. We report the balance uncertainty for completeness and transparency, and flag the heterogeneity term as the one that matters for design.

5. Comparison with the Literature

Reported EFB moisture values fall into three distinct regimes, and a meaningful comparison must keep them separate:

Material state	Moisture (%)	Source / note
Fresh EFB ex-mill	55-67	Rosli et al. (2017) report 55 % initial; fresh, undrained EFB up to ~67 %
Fresh EFB (very wet)	~70	Fibre/EFB streams quoted at ~70 % in mill mass balances
As-received / pressed (this work)	43.9	Sample 1, prepared frondlet fibre, partially drained
Air-dried laboratory sample	4.7-17	Abdullah & Sulaiman (2013) 4.68 %; Olisa & Kotingo (2014) 8.34 %; others 13-17 %

Table 2. Moisture of EFB by material state, showing why a single "moisture of EFB" figure is ambiguous.

Our measured dry solids of 56.08 % (moisture 43.92 %) is consistent with prepared, partially drained EFB. It is drier than fully fresh, undrained EFB ex-mill (which typically sits at 55-67 % moisture, i.e. 33-45 % DS) and very much wetter than the air-dried samples used for laboratory proximate, ultimate and calorific analyses (often 5-13 % moisture). The practical implication is direct: a freshly milled EFB stream carries roughly as much water as dry matter, and any thermal route must pay a substantial drying penalty before the fuel value of the solids can be realised, while a digestion route benefits from the moisture already present.

6. Summary of EFB Properties from the Literature

The following tables compile published values for EFB. Values are on a dry basis unless otherwise stated; ranges combine several independent studies and should be read as indicative of the spread expected from a heterogeneous agricultural residue rather than as a single "true" value.

6.1 Biochemical (lignocellulosic) composition

Component	Typical / range (% dry)	Representative sources
Cellulose (glucan)	38-60 (typically 43-45)	Abdullah & Sulaiman (2013); Wadchasit et al. (2020) 41.3-45.0; Rosli et al. (2017) 44.2; Najafpour et al. ~50
Hemicellulose	17-34 (typically ~33)	Abdullah & Sulaiman (2013) 16.8-22.1; Wadchasit et al. (2020) 25.3-33.8; Rosli et al. (2017) 33.5

Component	Typical / range (% dry)	Representative sources
Lignin	10-35 (typically 20-28)	Abdullah & Sulaiman (2013) 10.5-22.8; Wadchasit et al. (2020) 27.6-32.5; Rosli et al. (2017) 20.4
Glucan / Xylan / Arabinan	~35 / ~20 / ~3	Rosli et al. (2017), native unextracted OPEFB
Total extractives (water + ethanol)	up to ~12	Rosli et al. (2017): 0.10 % + 11.87 %; includes oils, waxes, free sugars
Residual oil	~1-7	Mill mass balances; ~1 % recyclable oil reported; frondlets notably oily

Table 3. Biochemical composition of EFB. Cellulose is the basis for fermentable-sugar and biogas potential; lignin is the recalcitrant, woody residue.

6.2 Proximate analysis

Property	Range (%)	Representative sources
Moisture (as analysed)	4.7-29	Abdullah & Sulaiman (2013) 4.68; Olisa & Kotingo (2014) 8.34; SOMCHE (2014) 13.3; IJEIR 29
Volatile matter	76-87	Abdullah & Sulaiman (2013) 76.85; Olisa & Kotingo (2014) 79.82
Fixed carbon	9.6-18	Abdullah & Sulaiman (2013) 18.07; Olisa & Kotingo (2014) 13.31
Ash	2.5-9.6	Abdullah & Sulaiman (2013) 5.19 (washed avg 2.48); Olisa & Kotingo (2014) 6.87; Sustainability (2023) 9.6
Total solids (TS)	~89.5	Sustainability (2023)
Volatile solids (VS)	~80.2 (VS/TS ~89 %)	Sustainability (2023); Wadchasit et al. (2020) VS/TS 89.4 %

Table 4. Proximate analysis of EFB. The high volatile matter (~80 %) and high VS/TS ratio (~89 %) explain EFB's suitability as both a combustion fuel and a digestion substrate.

6.3 Ultimate (elemental) analysis

Element	Range (% dry)	Representative sources
Carbon (C)	43.8-48.9	Olisa & Kotingo (2014) 43.80; Abdullah & Sulaiman (2013) 46.36; lit. 48.8-48.9
Hydrogen (H)	6.2-7.3	Olisa & Kotingo (2014) 6.20; Abdullah & Sulaiman (2013) 6.44
Nitrogen (N)	0.4-2.2	Olisa & Kotingo (2014) 0.44; Abdullah & Sulaiman (2013) 2.18
Sulphur (S)	0.09-0.92	Olisa & Kotingo (2014) 0.09; Abdullah & Sulaiman (2013) 0.92
Oxygen (O, by diff.)	38.9-42.7	Olisa & Kotingo (2014) 42.65; Abdullah & Sulaiman (2013) 38.91

Table 5. Ultimate analysis of EFB. Low sulphur is favourable for combustion; oxygen is normally reported by difference.

6.4 Calorific value

Property	Range	Representative sources
Higher heating value (HHV)	17.9-20.5 MJ/kg	Abdullah & Sulaiman (2013) 20.54; Najafpour et al. ~18.5 (4420 kcal/kg); IJEIR 17.85 (17,854 kJ/kg)

Property	Range	Representative sources
Lower heating value (LHV)	17.0-19.3 MJ/kg	Olisa & Kotingo (2014) 19.25 (19,250 kJ/kg); dry EFB ~17 (Wageningen / Blackwood)

Table 6. Calorific value of dry EFB. These values apply to dry solids; the as-received fuel value is far lower because of the ~44-67 % moisture that must first be evaporated.

6.5 Inorganic (ash) chemistry: potassium and chlorine

The inorganic fraction of EFB is dominated by potassium, with significant chlorine and sodium. These are precisely the elements that cause slagging, fouling and high-temperature corrosion in boilers, which is why water-washing of EFB before combustion is an active research topic.

Element / measure	Reported value	Representative sources
K₂O (of EFB)	3.08-3.65 %	Abdullah & Sulaiman (2013)
Potassium in ash	ash is ~30-40 % K ₂ O	Lim & Zaharah (2000), J. Oil Palm Res.
K removable by washing	71-95 %	Abdullah & Sulaiman (2013); washing literature
Chlorine (Cl)	significantly reduced by washing	Abdullah & Sulaiman (2013) - Cl, Na, K all leach readily
Sodium (Na)	up to ~96 % removable	Abdullah & Sulaiman (2013)
Total ash	2.5-9.6 %	see Table 4; washed EFB ~1-2.5 %

Table 7. Inorganic chemistry of EFB. The potassium- and chlorine-rich ash is both an agronomic asset (EFB returns potash to the plantation) and a combustion liability.

7. Discussion

Taken together, these properties explain why EFB is simultaneously attractive and awkward as a resource. The high volatile matter (~80 %), high VS/TS ratio (~89 %) and dry-basis calorific value of 18-20 MJ/kg make it a credible solid fuel and an excellent anaerobic-digestion substrate. The cellulose fraction (typically 43-45 %, occasionally reported near 60 %) underpins its potential as a feedstock for fermentable sugars. Yet two properties temper every route. First, the moisture: a fresh stream carries roughly its own dry weight in water, imposing a drying penalty on combustion and a transport penalty on any off-site use, while conversely making it well suited to wet conversion. Second, the inorganic chemistry: the potassium- and chlorine-rich ash that makes returned EFB a useful source of plantation potash is the same chemistry that fouls and corrodes boilers, motivating either washing pre-treatment or lower-temperature, non-combustion routes.

Our own measurement situates a real, mill-fresh, prepared sample within this picture at 56.08 % dry solids. More importantly for the series, it illustrates a methodological point: precise instruments produce precise numbers, but the honest uncertainty on a feedstock property is set by heterogeneity and sampling, not by the balance. Subsequent articles, which build on these baseline properties to examine conversion routes, will therefore treat replicate sampling rather than instrument precision as the controlling source of uncertainty.

8. Conclusion

The dry solids content of a fresh, prepared EFB sample from a West Kalimantan mill was measured as 56.08 % and the moisture as 43.92 %, with a balance-derived expanded uncertainty of ± 0.01 % ($k = 2$). This sits between fresh, undrained EFB (33-45 % DS) and air-dried laboratory samples (>87 % DS), and the dominant real-world uncertainty is feedstock heterogeneity rather than instrument precision. A compilation of published data gives indicative baselines for EFB: cellulose ~ 43 -45 %, hemicellulose ~ 33 %, lignin ~ 20 -28 %; volatile matter ~ 80 %, ash ~ 2.5 -9.6 %, VS/TS ~ 89 %; carbon ~ 44 -49 %, hydrogen ~ 6 -7 %, low sulphur (<1 %); HHV ~ 18 -20.5 MJ/kg; and a potassium- and chlorine-rich ash. These values form the reference baseline for the remaining articles in this series.

Author Contributions

D.S.: conceptualisation, methodology, validation, investigation, writing - original draft. A.B.: review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Note: This review draws on the reference library compiled for this project. Several entries report property ranges combined across multiple cited studies; where a single study is the source it is named explicitly.