Type of Contribution:
Editorial
Research Paper
Review Paper
Case Study

ENERGY: JURNAL ILMIAH ILMU-ILMU TEKNIK
Vol. 16, No. 2 (2026) pp 542-549
DOI: 10.51747/energy.v16i2.p542-549

E-ISSN: 2962-2565

This article contributes to:



Effect of Bentonite on the Combustion Behavior of Oil Palm Empty Fruit Bunch

Nur Chabibi[1]*, Shafiq Nurdin[1], Nurkholis Hamidi[2], Anas Mukhtar[3]

[1] Unisma Malang Polytechnic, Malang, 65144, **Indonesia**
[2] Department of Mechanical Engineering, Brawijaya University, Malang, 65145, **Indonesia**
[3] Mechanical Engineering Study Program, PGRI University of Banyuwangi, 68416, **Indonesia**
* chabibi@polisma.ac.id

Abstract

This study investigates the oxidative thermal decomposition (combustion) behaviour of oil palm empty fruit bunch (OPEFB) with and without a bentonite additive, characterized by thermogravimetric and differential thermal analysis (TG–DTA). Samples were heated from 30 to 1000 °C at 10 °C min^{-1} under a flowing air atmosphere (0.5 L min^{-1}). Under air, OPEFB burned in three stages: moisture release (<150 °C), combustion of volatile matter, and combustion of the residual char, leaving an inorganic ash residue. For raw OPEFB, the moisture loss was about 5.1%, the ignition temperature (tangent method) was about 230 °C, the volatile- and char-combustion DTG peaks occurred at approximately 251 and 400 °C, and the ash residue was 12.9%. Adding bentonite (OPEFB:bentonite = 1:0.1) raised the ignition temperature to about 250 °C, shifted the volatile-combustion peak to about 276 °C, and increased the ash residue to about 19.5%. These effects are interpreted physically: the inert aluminosilicate acts as a thermal ballast and an oxygen-transport barrier that delays ignition and volatile combustion, while its thermally stable framework dominates the residual ash. Because only a single heating rate was used, no isoconversional kinetic parameters were derived. The results provide baseline combustion-characterization data supporting the use of OPEFB as a solid fuel.

Keywords: Oxidative Thermal Decomposition, Combustion, TG–DTA, Bentonite additive, Oil Palm Empty Fruit Bunch.

Article Info
Submitted: 2026-07-29
Revised: 2026-09-16
Accepted: 2026-11-01
Published: 2026-11-04

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License

Publisher
Universitas Panca Marga

1. Introduction

Indonesia is one of the world's largest producers of palm oil, and its processing generates very large quantities of solid residues, of which oil palm empty fruit bunch (OPEFB) is among the most abundant; every tonne of fresh fruit bunch processed yields roughly 220–250 kg of OPEFB [1]. Its lignocellulosic nature and a higher heating value of about 15.4 MJ kg^{-1} [2] place OPEFB within the range of low-rank solid fuels and make it a promising renewable fuel, provided its combustion behavior is well understood [3].

From a physical standpoint, the combustion of a solid fuel in air is a sequence of coupled heat- and mass-transfer and reaction steps: the endothermic desorption of moisture, the release (devolatilization) and homogeneous gas-phase oxidation of volatile matter, and the heterogeneous (gas–solid) oxidation of the residual char [9], [10]. Thermogravimetric analysis (TGA) under an oxidizing (air) atmosphere resolves these steps as distinct mass-loss stages, from which characteristic parameters ignition temperature, peak temperature, and residual ash are obtained [3], [11]. Ignition is a thermal-balance phenomenon: self-sustaining combustion begins only when the local rate of heat release from oxidation exceeds the rate of heat loss to the surroundings [4].

Unlike coal, lignocellulosic biomass such as OPEFB has a high volatile-matter content and an oxygen-rich, reactive structure. Physically, the weaker, oxygenated bonds and the early, abundant release of volatiles lower the energy barrier to ignition, so biomass ignites and burns at markedly lower temperatures than coal [3], [12]. This high reactivity is advantageous for ignition but also makes the combustion sensitive to the mineral matter present in or added to the fuel [8].

The combustion behavior of solid fuels can be modified by additives. Catalytically active metal oxides can lower the ignition temperature and accelerate combustion [14], [17], whereas inert mineral additives act instead as thermal ballast and as physical barriers to oxygen transport, and they contribute non-combustible material to the ash [3]. Natural bentonite is an attractive, low-cost additive of the latter type an abundant aluminosilicate dominated by montmorillonite, a 2:1 layered Al_2O_3–SiO_2 structure [13], [14]. Indonesian and sodium-modified bentonite have been used as inexpensive catalysts or additives in biomass thermochemical conversion [1], [15], [16].

Despite this interest, data on the effect of bentonite on the combustion behavior of OPEFB characterized directly by TG–DTA in air remain limited. The present study therefore evaluates the oxidative thermal-decomposition (combustion) behavior of OPEFB, with and without bentonite, in order to (1) resolve the successive combustion stages and their characteristic temperatures, (2) assess the influence of

bentonite on the ignition temperature, peak temperatures, and ash residue, and (3) interpret these effects in terms of the underlying physical mechanisms.

2. Methods

2.1 Materials

Oil palm empty fruit bunch (OPEFB) was obtained as solid residue from palm oil processing. It was ground and sieved into a fine, homogeneous powder and oven-dried at approximately 50 °C for about 1 h prior to analysis. Natural bentonite powder was used as the additive. Two sample conditions were prepared: OPEFB without additive, and OPEFB mixed with bentonite at a mass ratio of 1:0.1 (OPEFB:bentonite). For reference, the HHV of raw OPEFB has been reported at approximately 15.4 MJ kg^{-1} [12], within the range of low-rank solid fuels.

2.2 Thermal analysis

The combustion behavior was characterized using a METTLER TOLEDO simultaneous thermal analyzer (TGA/DTA) at the Central Laboratory of Minerals and Advanced Materials, Faculty of Mathematics and Natural Sciences, Universitas Negeri Malang. Each sample was heated from 30 to 1000 °C at a constant heating rate of 10 °C min^{-1} under a flowing air atmosphere at 0.5 L min^{-1}, using α-Al_2O_3 as the DTA reference. The analyzer simultaneously recorded the thermogravimetric (TG) mass-loss curve, its derivative (DTG), and the differential thermal analysis (DTA) signal as functions of temperature. The initial sample masses were 15.8 mg (OPEFB) and 7.45 mg (OPEFB–bentonite).

2.3 Data analysis

The TG/DTG/DTA curves were used to determine, for each sample, the moisture loss below 150 °C, the ignition temperature (by the tangent method applied at the first combustion peak), the peak (DTG) temperatures of the volatile- and char-combustion stages, and the residual ash. Because the analysis was conducted under air, the process corresponds to oxidative thermal decomposition (combustion) rather than inert pyrolysis or gasification. Only a single heating rate was applied; consequently, no isoconversional kinetic analysis (e.g., Flynn–Wall–Ozawa) was performed, because valid isoconversional kinetics require thermograms at several heating rates [18], [19] [18,19]. The interpretation below is therefore qualitative rather than a kinetic determination.

3.Results and Discussion

3.1 Combustion behavior of OPEFB without additive

The TG and DTG curves of raw OPEFB heated in air are shown in **Figure 1**. Three successive stages are evident, consistent with the typical combustion profile of lignocellulosic biomass [6], [10]. The first stage, below about 150 °C, corresponds

to moisture release and accounts for a mass loss of approximately 5.1%. The second stage, with a sharp DTG peak at about 251 °C, corresponds to the devolatilization and combustion of volatile matter released from hemicellulose and cellulose. The third stage, with a broader DTG peak near 400 °C, corresponds to the combustion of the residual char. By the tangent method, the ignition temperature was about 230 °C a low value that reflects the high volatile-matter content and reactivity of biomass [3], [12] and the final ash residue was 12.9%. The DTA signal was exothermic across both combustion stages, confirming oxidative behavior.

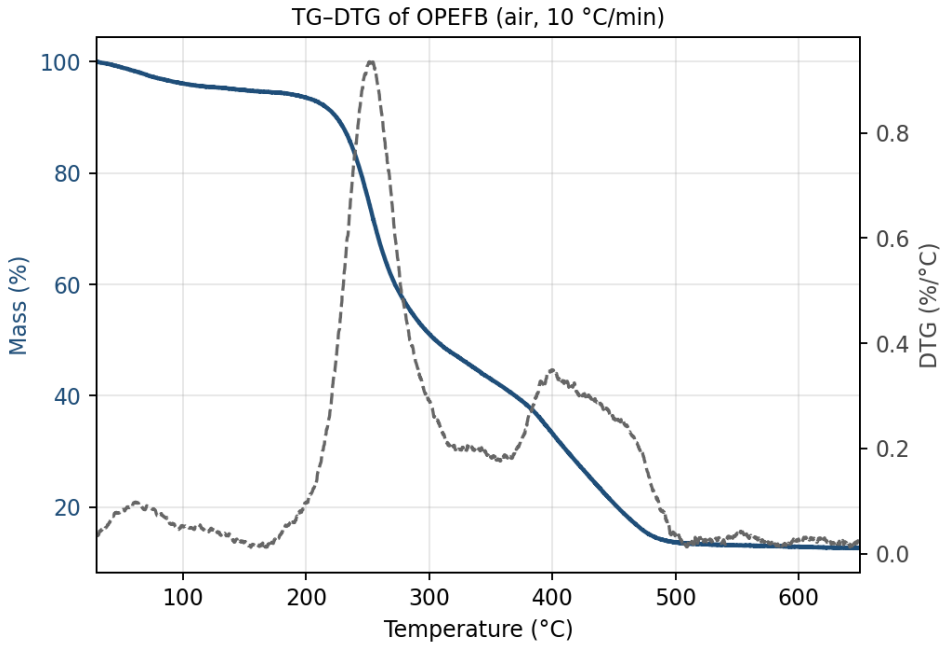


Figure 1. TG–DTG curves of OPEFB (without additive) in air at 10 °C min^{-1}

3.2 Combustion behavior of OPEFB with bentonite additive

The TG and DTG curves of the OPEFB–bentonite mixture are shown in **Figure 2**. The same three stages are observed, with a lower moisture loss (about 2.2%). The ignition temperature rose to about 250 °C and the volatile-combustion DTG peak shifted to about 276 °C, while the char-combustion peak remained near 407 °C. Most notably, the ash residue increased markedly, from 12.9% to about 19.5%.

3.3 Comparison and physical interpretation

Figure 3 compares the two samples, and the characteristic combustion parameters are summarized in **Table 1**. Adding bentonite raised the ignition temperature (from ~230 to ~250 °C), shifted the volatile-combustion peak upward (from ~251 to ~276 °C), and increased the ash residue from 12.9% to about 19.5%. A shift of the ignition and combustion temperatures to higher values together with an increase in residue upon addition of an aluminosilicate clay is consistent with previous reports on clay additives in solid-fuel combustion [8].

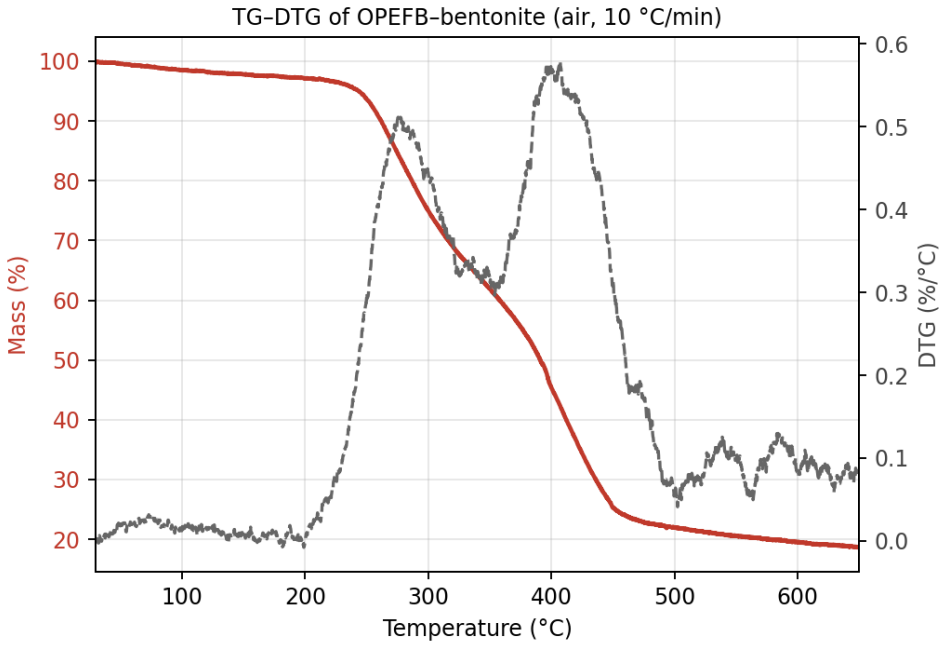


Figure 2. TG–DTG curves of OPEFB–bentonite (1:0.1) in air at 10 °C min^{-1}

These observations can be rationalized on physical grounds rather than as a change in intrinsic reactivity. First, bentonite acts as a thermal ballast: being chemically inert in this temperature range, it adds heat capacity but no exothermic heat release, so it dilutes the heat generated by the burning fraction and lowers the temperature that the fuel experiences at a given furnace temperature; ignition and the volatile-combustion peak are therefore shifted upward [8]. Second, the fine clay particles partly coat the biomass and char and obstruct the transport of oxygen to the reacting surface, further delaying oxidation [17]. Third, the thermally stable Si–O and Al–O framework of montmorillonite survives the heating program and remains almost entirely in the solid product, which is why the ash rises from 12.9% to about 19.5% [13], [14].

Table 1. Combustion parameters of OPEFB and OPEFB–bentonite (TG–DTA in air, 10 °C min^{-1})

Parameter	OPEFB	OPEFB–bentonite
Initial mass (mg)	15.8	7.45
Moisture loss, 30–150 °C (%)	5.1	2.2
Ignition temperature, Ti (tangent) (°C)	~230	~250
Volatile-combustion peak, Tp1 (°C)	~251	~276
Char-combustion peak, Tp2 (°C)	~400	~407
Ash residue at 600 °C (%)	12.9	19.5

Importantly, this behavior is opposite to that of catalytically active metal oxides, which lower the ignition temperature and accelerate combustion [14]: an inert aluminosilicate such as bentonite delays ignition and raises the ash rather than accelerating combustion, indicating a ballast-and-barrier role rather than a catalytic

one. Because only a single heating rate was used, no activation energy or kinetic parameters were determined; a full isoconversional analysis would require experiments at multiple heating rates.

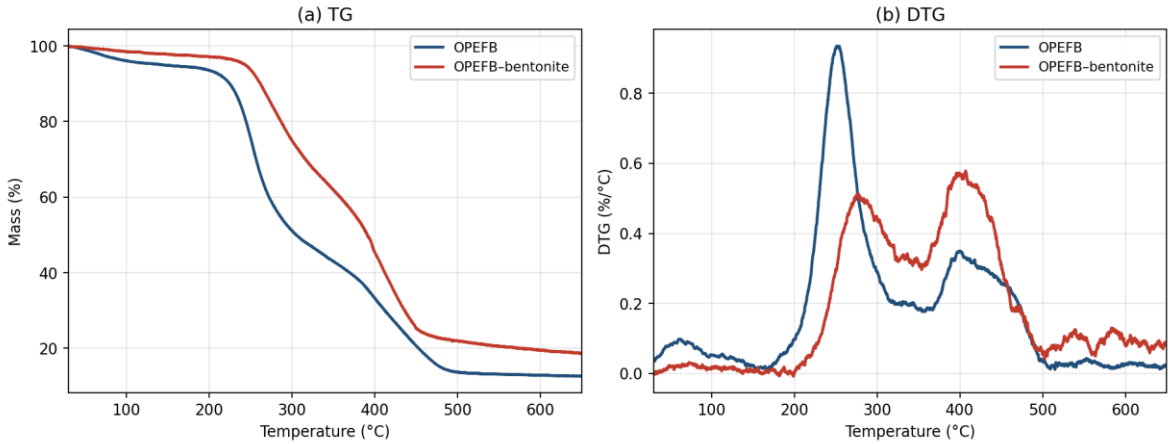


Figure 3. Comparison of (a) TG and (b) DTG curves of OPEFB and OPEFB–bentonite in air at 10 °C min^{-1}

4. Conclusion

The oxidative thermal-decomposition (combustion) behavior of OPEFB in air was characterized by TG–DTA, with and without a bentonite additive. Raw OPEFB burned in three stages moisture release (~5.1%), volatile combustion (DTG peak ~251 °C), and char combustion (DTG peak ~400 °C) with a low ignition temperature (~230 °C, tangent method) reflecting its high volatile-matter content, and an ash residue of 12.9%. Adding bentonite (1:0.1) raised the ignition temperature to ~250 °C, shifted the volatile-combustion peak to ~276 °C, and increased the ash residue to ~19.5%. These effects are consistent with bentonite acting as an inert thermal ballast and an oxygen-transport barrier that delays ignition and volatile combustion, while its thermally stable aluminosilicate framework dominates the residual ash, rather than with any catalytic enhancement. Because a single heating rate was used, no kinetic parameters were determined; multiple heating rates would be required for isoconversional kinetic analysis. Overall, the results provide baseline combustion-characterization data for OPEFB and show that low-cost bentonite measurably modifies its combustion profile and ash yield.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding - No funding information from the authors.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

References

[1] Aprianti, N., Faizal, M., Said, M., & Nasir, S. (2021). Catalytic gasification of oil palm empty fruit bunch by using Indonesian bentonite as the catalyst. Journal of Applied Engineering Science, 19(2), 334–343. https://doi.org/10.5937/jaes0-28781

[2] Erdiwansyah, Mahidin, Husin, H., Nasaruddin, Khairil, Zaki, M., & Jalaluddin. (2023). Comparative analysis of HHV and LHV values of biocoke fuel from palm oil mill solid waste. Case Studies in Chemical and Environmental Engineering, 8, 100525. https://doi.org/10.1016/j.cscee.2023.100525

[3] Kuswa, F. M., Putra, H. P., Prabowo, Darmawan, A., Aziz, M., & Hariana, H. (2024). Investigation of the combustion and ash deposition characteristics of oil palm waste biomasses. Biomass Conversion and Biorefinery, 14(19), 24375–24395. https://doi.org/10.1007/s13399-023-04418-z

[4] Bin Nur Taufiq, Muhammad, Z. H., Rulianda, P. W., & Mariani, S. (2024). Experimental study of combustion chamber performance utilizing biochar from empty fruit bunch (EFB) as fuel with variation in excess air. E3S Web of Conferences, 519, 01001. https://doi.org/10.1051/e3sconf/202451901001

[5] Srasri, S., Bhudsarakam, N., Limsutthiphong, P., Ratanapitag, T., & Julsereewong, A. (2022). Design of step grate firing by utilizing palm empty-fruit-bunch fuel for industrial steam boiler construction. Energy Reports, 8, 275–282. https://doi.org/10.1016/j.egyr.2021.11.142

[6] Pansawati, I. S., Prabowo, B., Cahyono, R. B., & Budhijanto, W. (2024). Kinetic and combustion characteristics of oil palm empty fruit bunch biochar using thermogravimetric analysis. Jurnal Teknosains, 13(2). https://doi.org/10.22146/teknosains.89413

[7] Sisuthog, W., Attanatho, L., & Chaiya, C. (2022). Conversion of empty fruit bunches (EFBs) by hydrothermal carbonization towards hydrochar production. Energy Reports, 8, 242–248. https://doi.org/10.1016/j.egyr.2022.10.183

[8] Wnorowska, J., Ciukaj, S., & Kalisz, S. (2021). Thermogravimetric analysis of solid biofuels with additive under air atmosphere. Energies, 14(8), 2257. https://doi.org/10.3390/en14082257

[9] Jia, G. (2021). Combustion characteristics and kinetic analysis of biomass pellet fuel using thermogravimetric analysis. Processes, 9(5), 868. https://doi.org/10.3390/pr9050868

[10] Arromdee, P., & Ninduangdee, P. (2023). Combustion characteristics of pelletized-biomass fuels: a thermogravimetric analysis and combustion study in a fluidized-bed combustor. Energy, Ecology and Environment, 8, 69–88. https://doi.org/10.1007/s40974-022-00263-4

[11] Yuan, Y., He, Y., Tan, J., Wang, Y., Kumar, S., & Wang, Z. (2021). Co-combustion characteristics of typical biomass and coal blends by

thermogravimetric analysis. Frontiers in Energy Research, 9, 753622. https://doi.org/10.3389/fenrg.2021.753622

[12] El-Sayed, S. A., Khass, T. M., & Mostafa, M. E. (2023). Thermal degradation behaviour and chemical kinetic characteristics of biomass pyrolysis using TG/DTG/DTA techniques. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-023-03926-2

[13] Karod, M., Hubble, A. H., Maag, A. R., Pollard, Z. A., & Goldfarb, J. L. (2022). Impact of bentonite clay on in situ pyrolysis vs. hydrothermal carbonization of avocado pit biomass. Catalysts, 12(6), 655. https://doi.org/10.3390/catal12060655

[14] Denison, S. B., Umbriac, D. J., Charco, E., Xu, X., & Goldfarb, J. L. (2023). Pyro-catalytic degradation of pyrene by bentonite-supported transition metals. Environmental Science & Technology, 57(38), 14373–14383. https://doi.org/10.1021/acs.est.3c04487

[15] Irawan, D., Wijayanti, W., Wahyudi, S., Kusumo, H. N. R. A., Yani, A., & Wardana, I. N. G. (2025). Enhanced hydrogen production from biomass pyrolysis using surfactant-modified Na-bentonite catalyst. ASEAN Journal of Science and Engineering, 5(3), 539–558. https://doi.org/10.17509/ajse.v5i3.88898

[16] Irawan, D., Wijayanti, W., Wahyudi, S., & Wardana, I. N. G. (2025). Modification effects of Na-bentonite catalyst with organic compounds increasing hydrogen production from biomass pyrolysis. Case Studies in Chemical and Environmental Engineering, 11, 101206. https://doi.org/10.1016/j.cscee.2025.101206

[17] Wang, W., Lemaire, R., Bensakhria, A., & Luart, D. (2022). Review on the catalytic effects of alkali and alkaline earth metals (AAEMs) on the pyrolysis of lignocellulosic biomass and on the co-pyrolysis of coal with biomass. Journal of Analytical and Applied Pyrolysis, 163, 105479. https://doi.org/10.1016/j.jaap.2022.105479

[18] Fischer, O., Lemaire, R., & Bensakhria, A. (2024). Thermogravimetric analysis and kinetic modeling of the pyrolysis of different biomass types by means of model-fitting, model-free and network modeling approaches. Journal of Thermal Analysis and Calorimetry, 149, 10941–10963. https://doi.org/10.1007/s10973-023-12868-w

[19] Wang, W., Lemaire, R., Bensakhria, A., & Luart, D. (2023). Thermogravimetric analysis and kinetic modeling of the co-pyrolysis of a bituminous coal and poplar wood. Chinese Journal of Chemical Engineering, 58, 53–68. https://doi.org/10.1016/j.cjche.2022.10.015

[20] Rusdianasari, Utarina, L., Kalsum, L., Wulandari, D., & Bow, Y. (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). https://doi.org/10.29165/ajarcde.v7i1.237