Utilization of Used Bleaching Clay in Pellet Fuel Production with Torrefied Oil Palm Fronds

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Torrefaction oil palm fronds was studied as a renewable biomass resource for efficient and sustainable pellet fuel production. Employing microwave heating during torrefaction, the process optimized the conditions to enhance the fuel properties. At 300 °C for 40 minutes, the torrefied oil palm fronds exhibited a remarkable rise in net calorific value to 23 MJ/kg, accompanied by a substantial increase in fixed carbon content to 46%. These enhancements signify a significant boost in energy content and carbon richness, which is crucial for cleaner and greener energy solutions. Comparing pellet fuels derived from raw and torrefied biomass, a striking difference in calorific values was observed. While raw biomass pellets reached 12.24 MJ/kg, their torrefied counterparts achieved an impressive 18.40 MJ/kg. This undeniable advantage highlights the effectiveness of torrefaction in elevating energy output. To optimize the composition of the pellet fuel, an ideal mass proportion of torrefied oil palm fronds and used bleaching clay was identified as 70:30. This blend resulted in the highest recorded calorific value, further endorsing the viability of the approach. In conclusion, torrefaction at 300 °C for 40 minutes proved to be a potent technique for enhancing oil palm fronds as a valuable source of pellet fuel. These findings underscore its potential to revolutionize renewable energy production, promoting sustainability and mitigating environmental impact.

DOI: 10.15376/biores.18.4.6986-7002

Keywords: Used bleaching clay (UBC); Oil palm fronds (OPF); Reactivation; Pellet fuel; Torrefaction

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INTRODUCTION

Palm oil crops provide both food and fuel. In 2019, the oil palm plantation area in Thailand was 6,102,852 m^2, yielding 16,408,440 tons of fruit oil palm (DIT 2019). The forecasting of palm oil consumption by consumers increased from 1.02 million tons in 2015 to 1.35 million tons in 2026 (an increase of 3% per year), while its use for renewable energy over the same period grew from 1.32 to 2.60 million tons (an increase of 7% per year) (DIT 2019). Palm oil is a refined form of extract from oil palm fruit. The traditional palm oil refining processes involve four major steps, which are degumming, bleaching, neutralization, and deodorization (Saputro *et al.* 2020).

Bleaching is particularly important in palm oil refining. The purpose of bleaching is to adsorb impurities from crude palm oil, mostly both saturated and unsaturated fats

(Nursulihatimarsyila *et al.* 2010). The bleaching process for one mill, New Biodiesel Co., Ltd., generates an average amount of waste in the form of used bleaching clay, about 4,000 tons per month. Used bleaching clay often contains 20 to 40% (w/w) of residual oil and other organic matter, which can rapidly oxidize to the point of spontaneous ignition due to catalysis by the clay minerals. Therefore, it is classified as hazardous waste in many countries (Mu *et al.* 2019). Thus, it must be disposed of as industrial waste and managed as governed by the laws, typically ending up in a landfill. The use as an alternative fuel for high-heat furnaces, in composting, or as a component in soil conditioner, incurs operation, transportation, and disposal costs (Kittithammavong *et al.* 2016). Many studies have attempted to improve the effectiveness of bleaching clay or to extract the residual oil and regenerate the used bleaching clay (Mahramanlioglu *et al.* 2010).

It has been forecasted that the global energy demand will increase 28% by the year 2040. This increase causes concerns regarding climate change and energy security, and it motivates the search for sustainable and renewable energy sources (Owusu and Asumadu-Sarkodie 2016; Manouchehrinejad *et al.* 2021). Renewable energy sources, such as wood pellets, have become increasingly important in the last decade because of the phasing-out of fossil fuels (Luo *et al.* 2020). Co-firing wood pellets in coal-fired power plants can contribute to a future that is less carbon-intensive, while retaining an adequate capacity for energy production (Visser *et al.* 2020). In some power plants in the UK and continental Europe, wood pellets are used as the main solid biofuel (Goerndt *et al.* 2013).

Torrefaction technology, known for its mild reaction conditions and conducted in an oxygen-free environment at temperatures between 200 and 300 °C (Fuad *et al*. 2019), has gained significant interest in pellet production over the last decade. This promising method enables the production of stable biomass pellets with enhanced energy density, high gross calorific value, hydrophobicity, and a reduced global warming potential (Chen and Kuo 2011; Li *et al*. 2012; Chotikhun *et al*. 2022). Previous researchers chose microwave torrefaction due to its unique advantages over conventional torrefaction methods. The rapid reactions, uniform heating, substantial energy savings, fast internal heating, prevention of secondary reactions, energy density of biomasss and decreased its grinding energy, and ability to utilize large-sized feedstock (Fund *et al*. 2019; Ren *et al*. 2012; Jamaluddin *et al*. 2013; Valdez *et al*. 2021) align well with our objective of efficient and sustainable pellet fuel production.

Because of the outstanding fuel properties of used bleaching clay, it is reasonable to expect that it could be utilized in a pellet fuel. The important fuel properties include heating value, humidity, volatile matter content, fixed carbon content, and ash content. The heating value of used bleaching clay is approximately 7.28 to 11.4 MJ/kg (Srisang *et al*. 2017). However, a pellet made of only used bleaching clay does not meet the criteria specified in product standards. Therefore, further research has been conducted to find a suitable biomass to be torrefied and used in pellet fuels in combination with used bleaching clay. The oil palm fronds are considered waste biomass from the oil palm industry, and are available in large amounts. Sukiran *et al.* (2017) reported in Malaysia that up to 52 million tons of oil palm fronds are produced each year, but only 4 million tons are used. The oil palm fronds' key fuel properties are 3,750 cal/g heat value, 62.0 to 77.0% moisture content, 83.6 to 88.3% volatile matter, 3.2 to 14.8% stable carbon, and 3.2 to 3.8% ash content (Sukiran *et al.* 2017). Therefore, this study assessed the reuse of used bleaching clay from palm oil refining with torrefied oil palm fronds for making a pellet fuel.

EXPERIMENTAL

Materials

Preparation of raw materials

The frond biomass used in this study was sourced from oil palm trees (*Elaeis guineensis*) approximately 15 years old, located in Khun Thale subdistrict, Mueang district, Surat-Thani province, Thailand. The leaves in OPF were cut off before chipping in an industrial drum chipper (YGX216, Henan Shindery Machinery Equipment Co., Ltd., Henan, China). The chips were then dried in an electric oven at 70 °C until the moisture content was less than 10%. The dry sample was crushed by a grinder and sieved to a particle size below 9 mm.

Used bleach clay (UBC) was obtained from New Biodeisel Co., Ltd. (Surat Thani, Thailand). It was dried in a hot-air oven for 2 h and 105 ℃ to reduce the moisture content, which was then less than 5 wt%.

Set-up of the torrefaction system

A schematic diagram of the microwave torrefaction reactor used in this study is shown in Fig. 1. The microwave cavity had stainless steel walls, for a width of 0.22 m, a depth of 0.22 m, and a height of 0.31 m. The Duran reactor vessel had 2,000 mL volume. The magnetron was rated for 1,000 Watts. Nitrogen gas (N_2) was used as the carrier gas supplied to the reactor vessel at its bottom. The flow rate of N_2 was controlled with a control valve and measured with a flow meter. The temperature of a biomass sample during experimental runs was measured with a K-type thermocouple equipped with a stainless-steel probe shield, and the temperature in the reactor was feedback controlled by SHIMAX model MAC3D-MSF-EN-NRN.

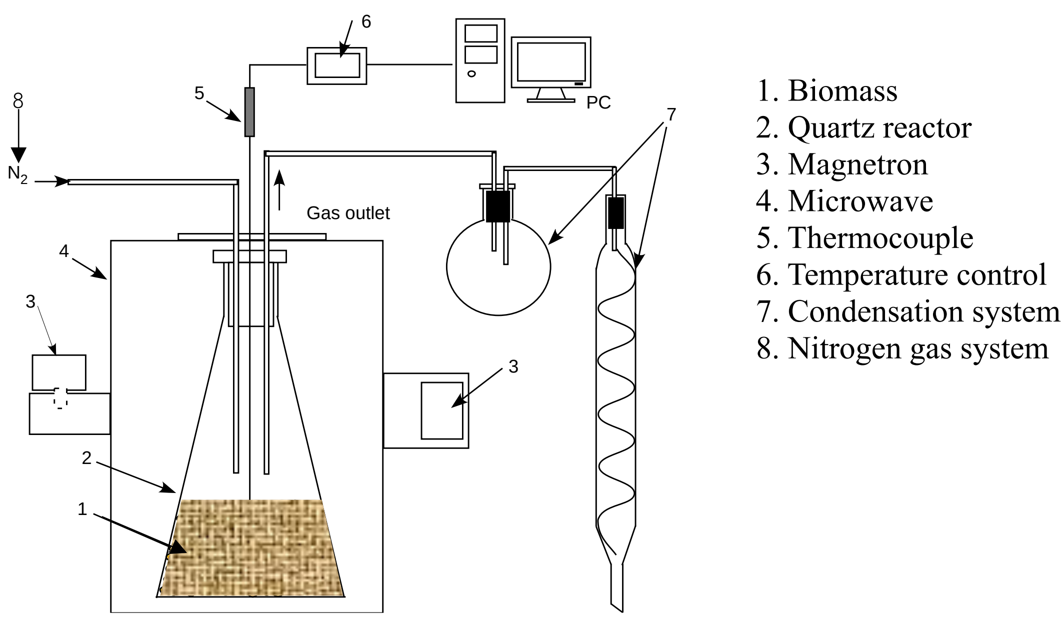

Fig. 1. Schematic of microwave heated torrefaction system

Set-up of the pelleting machine

The eventual fuel samples were densified and formed into pellets with an electric flat die wood pellet mill (KN-D-200, Zhengzhou Known Imp. & Exp. Co., Ltd., Henan, China) with 7.5 hp (380 V) motor and a capacity of 100 to 150 kg/h. The pellet diameter was approximately 6 mm. The raw material batches run to pellets were 5 kg. The moisture content of samples before pelletizing was controlled to 12 to 15% (Chotikhun *et al.* 2022).

Test Standards

The pellet fuel was prepared with 6 recipes, and each was tested for fuel properties, such as net calorific value, proximate analysis (moisture, ash, fixed carbon, and volatile matter), ultimate analysis (C, H, O, N, and S elements), mechanical durability, length and diameter, and bulk density in accordance with the Thai standard for “Solid biofuels – biomass pellets (non – woody biomass)” (TIS No. 2772-2560), and ISO/TS 17225-8 (2016) Solid biofuels - Fuel specifications and classes (Part 8 : Graded thermally treated and densified biomass fuels) (ISO 17225-8 (2016)).

Methods

Torrefaction process

In this study, 100 g oil palm fronds per batch were torrefied in a microwave torrefaction reactor under operating conditions specified for each batch run in the experimental design. The oil palm fronds were fed into the reactor chamber *via* the open top. N_2 at 2 L/min was supplied to the reaction chamber for 2 min to ensure an inert atmosphere. The oil palm fronds were then heated from ambient temperature to the set-point temperature, controlled with the temperature controller (SHIMAX) to 300 °C, and during this period the flow rate of N_2 was maintained at 2 L/min. The run times tested were 20, 40, and 60 min, with the timer starting when the reactor reached the desired temperature.

After torrefaction, net calorific value and proximate composition were measured, to choose the best torrefaction conditions for achieving the highest net calorific value. Then torrefaction was performed in this near-optimal condition until the desired amount was obtained for pelletizing the experimental mixes with used bleach clay.

Pelleting Process

The used bleaching clay (UBC) and oil palm frond (OPF) were mixed to a total weight of 1 kg with UBC:OPF ratio 30:70, 50:50, or 70:30 (Srisang *et al.* 2017). Similar mixes were made with torrefied oil palm frond (TOPF), with UBC: TOPF ratio 30:70, 50:50, or 70:30, as shown in Table 1 (Srisang *et al*. 2017).

Each blend was compressed in the pelleting machine operated at 100 °C, and the pellets were cut to 3 to 7 cm lengths.

Table 1. Recipes Used to Mix Bleaching Clay with TOPF/OPF

Sample	Percent (by Weight)		
	UBC	OPF	TOPF
UBC: OPF	30	70	0
UBC: OPF	50	50	0
UBC: OPF	70	30	0
UBC: TOPF	30	0	70
UBC: TOPF	50	0	50
UBC: TOPF	70	0	30

RESULTS AND DISCUSSION

Characteristics of Used Bleaching Clay and Oil Palm Frond, and Torrefied Oil Palm Frond

Physical Characteristics

The appearances of the raw materials are shown in Fig. 2. The used bleaching clay (UBC) was gray, viscous, and partially agglomerated due to the residual palm oil within the pore structure of UBC. The oil palm frond (OPF) after drying turned from green to brown. When thoroughly ground, fibrous component was dominant, while there also was some fine dust-like powder. The yield of torrefied oil palm frond (TOPF) was about 50% of the OPF, and the color changed over time. The TOPF from 300 °C for 20 min was mostly dark brown but in some cases still colored like OPF. The TOPF subjected to 300 °C for 40 minutes turned entirely black, signifying more intense torrefaction and greater weight loss. Similarly, the TOPF baked at 300 °C for 60 min also exhibited a predominantly black color, akin to the 40-minute TOPF. Other physical attributes showed no direct variation with torrefaction duration. This aligns with Kongto *et al*.'s (2021) findings, suggesting minimal impact of torrefaction duration on biomass characteristics.

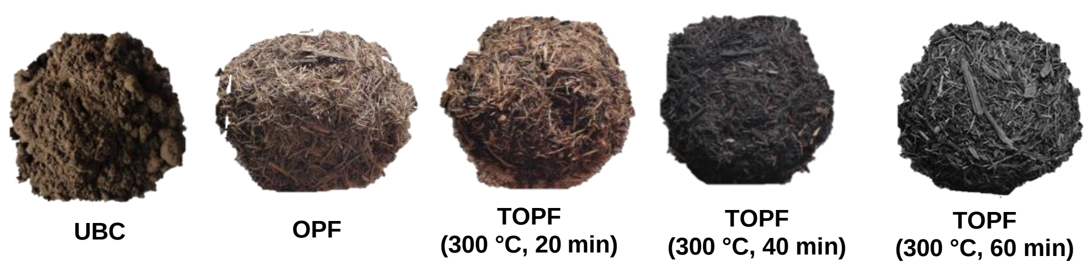

Fig. 2. Images of raw materials and TOPF

Net calorific value and proximate analysis

Table 2 displays the net calorific value and the outcomes of proximate analyses. The net calorific values of used bleaching clay (UBC) and oil palm frond (OPF) were 9.20 and 16.70 MJ/kg, respectively. The net calorific values were 21.12, 23.01, and 22.35 MJ/kg for torrefied oil palm frond (TOPF) processed at 300 °C for 20, 40, and 60 min, respectively. The values clearly increased from that for OPF. This is in line with studies by Kongto *et al.* (2021) and Brotto *et al.* (2022), where it was amply demonstrated that the net calorific value of biomass is increased by torrefaction. Torrefied biomass has a higher heating value than raw biomass because of the reduction in H and O elements from loss of moisture and of volatile matter (Fig. 3). A more complete torrefaction increases the fixed carbon (FC) along with the calorific value. Here, the torrefaction condition with the highest 23.01 MJ/kg calorific value, namely 300 °C for 40 min, was chosen for making the torrefied component in a pellet fuel.

The results from proximate analysis are presented in Table 2. It can be seen that during torrefaction as the run time increased, both MC and VM dropped, indicating the loss of moisture and volatiles. The MC of OPF decreased from 9.45% to 1.70% (300 °C for 20 min), 1.75% (300 °C for 40 min), and 1.70% (300 °C for 60 min). The temperature, run time, and heating rate all affect how much VM is released from the biomass (Singh *et al.* 2020). Increased torrefaction temperature or a longer duration tend to decrease moisture content (MC) and volatile matter (VM), whereas fixed carbon (FC) and ash content (AC) tend to increase, respectively. The lower VM and higher FC improved the fuel ratio of TOPF (Fig. 4), which results in stable and complete combustion (Wang *et al.* 2021). Additionally, the rise in net calorific value of torrefied biomass is caused by the change in FC. When studying the effects of torrefaction temperature on the aggregate components in TOPF, it was found that the lignocellulosic components, especially hemicellulose and cellulose, decompose faster at higher temperatures. The lignin decomposes much more slowly below 300 °C, so thermal decomposition of hemicellulose and cellulose gives a higher fuel ratio for TOPF (Wang *et al.* 2018).

Table 2. Net calorific Value and Proximate Analyses of Raw Materials and Torrefied Oil Palm Frond

Sample Type	Moisture content (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash Content (%)	Net Calorific Value (MJ/kg)
UBC	1.14 ± 0.09	11.53 ± 0.12	1.01 ± 0.08	86.32 ± 0.05	9.20 ± 0.22
OPF	2.64 ± 0.05	76.19 ± 0.26	17.99 ± 0.23	3.18 ± 0.04	16.70 ± 0.08
TOPF (300 °C, 20 min)	6.62 ± 0.15	63.9 ± 0.75	25.34 ± 0.97	4.09 ± 0.11	21.12 ± 0.14
TOPF (300 °C, 40 min)	1.63 ± 0.02	46.43 ± 0.83	46.06 ± 1.39	5.87 ± 0.59	23.01 ± 0.04
TOPF (300 °C, 60 min)	2.04 ± 0.12	53.37 ± 0.43	38.94 ± 0.52	4.66 ± 0.47	22.35 ± 0.21

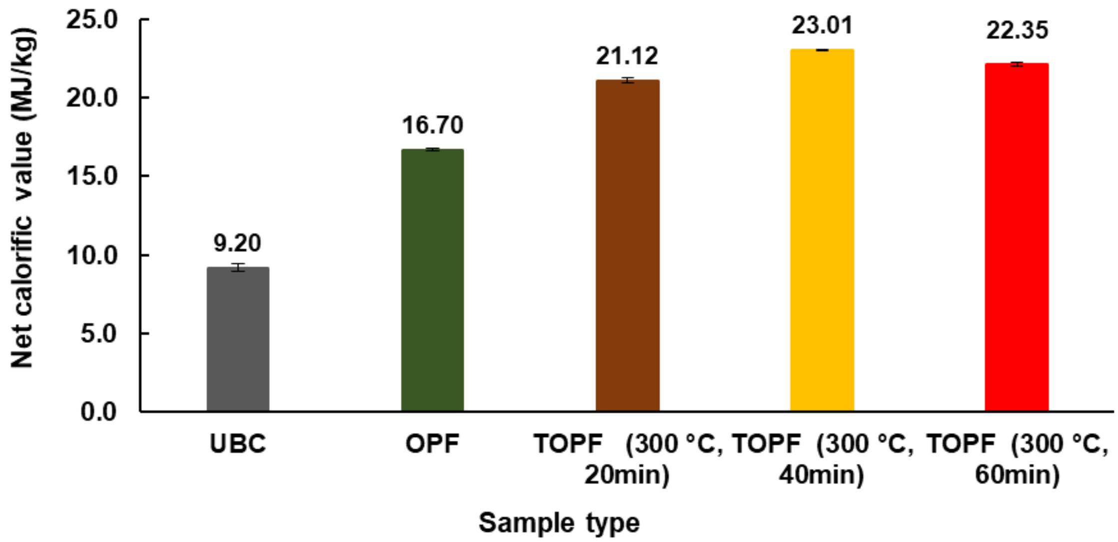

Fig. 3. Net calorific value of raw materials and torrefied oil palm frond

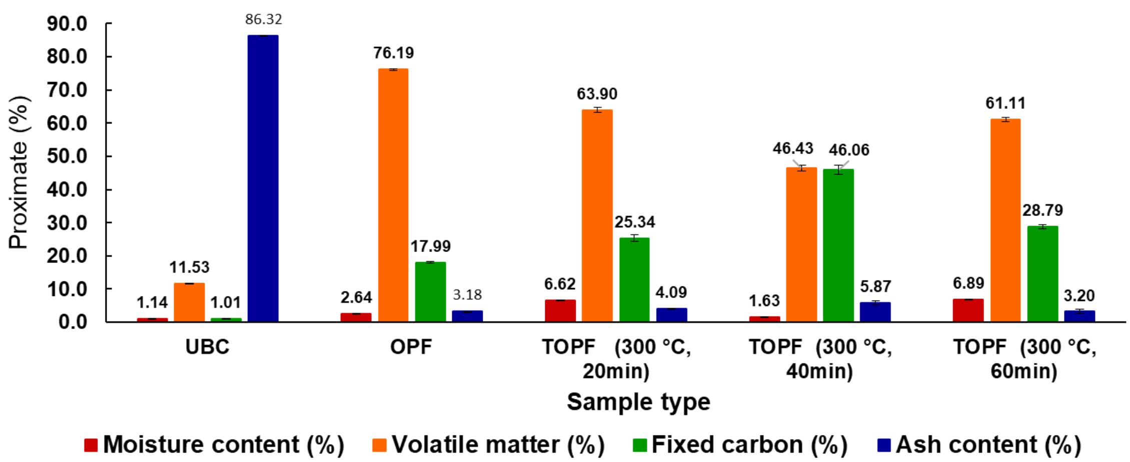

Fig. 4. Proximate analyses of raw materials and torrefied oil palm frond

Fuel Ratio (FC/VM)

The fuel ratio is an important parameter characterizing fuels for combustion, indicative of the type of combustion that may occur (Khempila 2022). From Table 3 it can be seen that the fuel ratios of the raw materials were small, while torrefaction in all cases increased the fuel ratio.

Generally, biomasses have a poor fuel ratio, giving rise to more flames during combustion than from burning coal and a shorter burning time. In contrast, the lower volatile matter and the higher fixed carbon in torrefied oil palm frond (TOPF) provide more stable combustion (Khempila 2022). The fuel ratio of coal is in the range of 0.5 to 3.0 (Singh *et al.* 2020). The highest fuel ratio for TOPF (300 °C, 40 min) was 0.99, as shown in Fig. 5, and this reaches the range for coal, indicating that the solid product produced is suitable for combustion.

Table 3. Fuel Ratios of Raw Materials and Torrefied Oil Palm Frond

Sample Type	Volatile Matter (%)	Fixed Carbon (%)	Fuel Ratio (FC/VM)
UBC	11.53	1.01	0.09
OPF	76.19	17.99	0.24
TOPF (300 °C, 20 min)	63.9	25.34	0.40
TOPF (300 °C, 40 min)	46.43	46.06	0.99
TOPF (300 °C, 60 min)	61.11	28.79	0.47

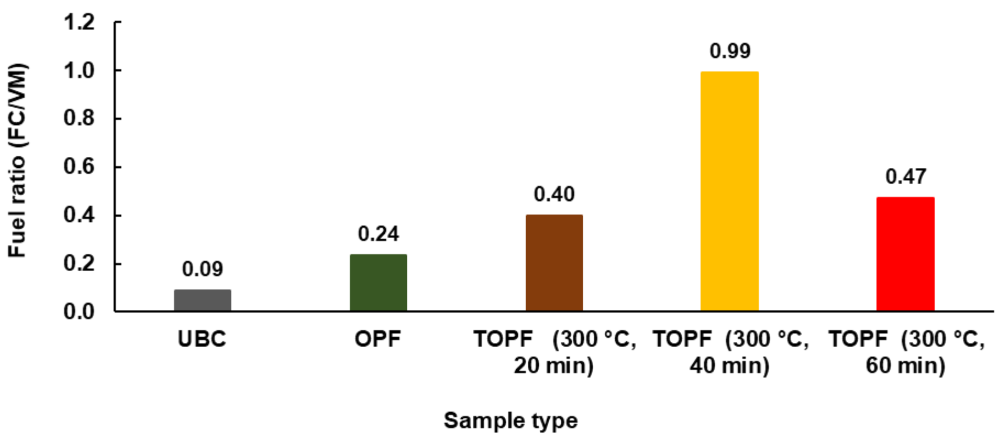

Fig. 5. Fuel ratios of raw materials and torrefied oil palm frond

Mass Yield

Mass yield after torrefaction was calculated. The energy yield (EY) indicates the energy obtained after torrefaction and correlates with the mass yield and the net calorific value. Energy densification (ED) indicates the energy density relative to raw biomass before torrefaction. Table 4 clearly shows that all these quantities were dependent on the torrefaction conditions.

Table 4. Mass Yield of Torrefied Oil Palm Frond

Sample type	LHV	HHV	MY (%)	EY (%)	ED (GJ/m^3)
OPF	14.81	14.04	-	-	-
TOPF (300 °C, 20 min)	18.40	22.62	64.50	103.90	1.61
TOPF (300 °C, 40 min)	25.97	30.72	49.00	66.55	1.36
TOPF (300 °C, 60 min)	19.91	25.46	41.00	33.98	0.83

Characteristics of Pellet Fuels

Physical characteristics of pellet fuels

There was a noticeable difference in color and texture of the two types of pellet fuels, namely those made with raw or torrefied biomass (Fig. 6). With raw biomass the pellets had a grayish-green color, matching that of the raw material used. In contrast, the pellet fuels made with torrefied biomass appeared grayish black with somewhat shiny smoothness, and apparent homogeneity. A greater proportion of OPF resulted in a more inhomogeneous pellet appearance.

a-1
ratio OPF: UBC = 30:70

a-2
ratio OPF: UBC = 50:50

a-3
ratio OPF: UBC = 70:30

a. Non-torrefied pellet fuel

b-1 ratio
TOPF: UBC = 30:70

b-2 ratio
TOPF: UBC = 50:50

b-3 ratio
TOPF: UBC = 70:30

b. Torrefied pellet fuel

Fig. 6. Appearances of pellet fuels made with raw or torrefied biomass mixed with UBC

Net calorific value and proximate analysis

The properties from testing of biomass pellet fuel made with used bleaching clay (UBC) and either OPF or TOPF are summarized in Table 5. The calorific value was the highest at 30:70 ratio of UBC:OPF (or of UBC:TOPF) reaching 12.24 MJ/kg (or 18.40 MJ/kg). This is because the net calorific value of OPF was higher than that of UBC, so the largest biomass content gave the largest calorific value for the mix (Fig. 7). A high net calorific value shows fuel potential. The results show that the net calorific value increases with OPF fraction, and Srisang *et al.* (2017) have indicated this should happen when mixing ingredients of different calorific values.

The properties of pellet fuels from TOPF and UBC (Fig. 7) show their net calorific values. The TOPF:UBC at 70:30 (18.40 MJ/kg) passed the biomass pellet standard ISO/TS 17225-8 (2016) for fuel use, due to its high net calorific value. The net calorific value increased with TOPF content.

In proximate analysis, the moisture contents (MC) of both pellet fuels were non-standard. The MC of pellet fuel made with raw biomass was higher than those of all cases with torrefied biomass, because raw OPF had a high moisture content. A pellet fuel needs a low MC for hardness and strength in handling, and for easy ignition (Khempila 2022).

In volatile matter (VM) content, the pellets made with raw biomass were also higher than those made with torrefied biomass, in all cases (Fig. 8). For fixed carbon (FC), the torrefied biomass gave pellet fuel that was remarkably higher than pellets with raw biomass, in all cases. Considering the ash contents (AC) in Table 5, they reflected the amount of used bleaching clay in the pellets. According to Srisang *et al.* (2017), used bleaching clay has a relatively high AC compared to biomasses, because the clay mainly consists of montmorillonite mineral, and this component dominates in AC of the pellet fuel (Cao *et al.* 2020).

Table 5. Net Calorific Value and Proximate Analyses of Pellet Fuel

Sample Type	Moisture Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash Content (%)	Net Calorific Value (MJ/kg)
OPF: UBC (30:70)	3.93 ± 0.06	36.62 ± 0.36	8.31 ± 0.32	51.14 ± 0.06	11.46 ± 0.14
OPF: UBC (50:50)	6.14 ± 0.04	38.76 ± 0.29	10.06 ± 0.34	35.04 ± 0.10	11.48 ± 0.14
OPF: UBC (70:30)	9.94 ± 0.08	33.78 ± 0.24	8.40 ± 0.16	17.87 ± 0.14	12.24 ± 0.07
TOPF: UBC (30:70)	1.10 ± 0.21	31.97 ± 0.21	21.22 ± 0.20	39.32 ± 0.20	12.87 ± 0.05
TOPF: UBC (50:50)	1.16 ± 0.28	32.22 ± 0.96	19.99 ± 0.19	38.65 ± 0.92	16.21 ± 0.09
TOPF: UBC (70:30)	1.44 ± 0.25	30.32 ± 0.38	23.49 ± 0.16	35.14 ± 0.80	18.40 ± 0.03

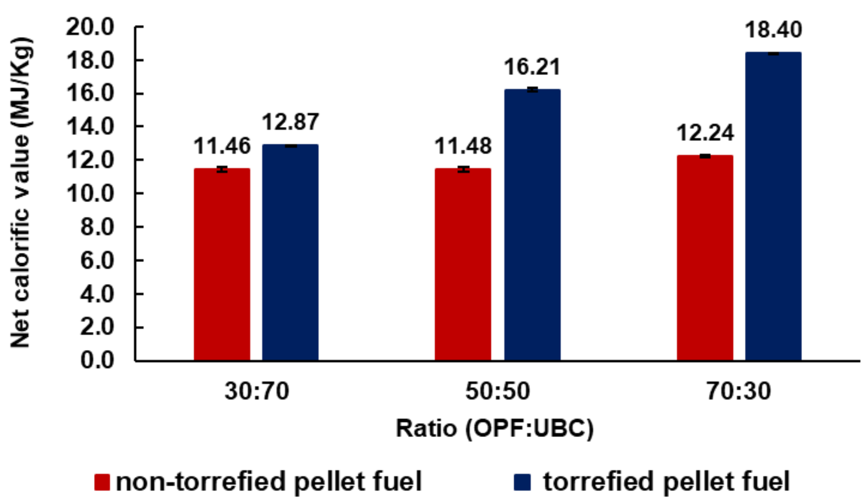

Fig. 7. Net calorific value of pellet fuels made with raw or torrefied biomass

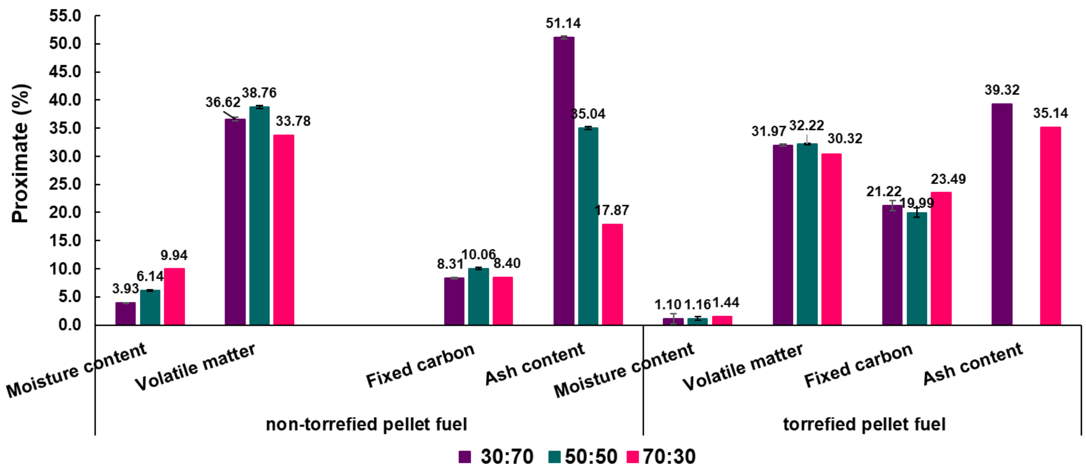

Fig. 8. Proximate analyses of pellet fuels made with raw and torrefied biomass

Properties of High Net Calorific Value Pellet Fuel

An examination of the calorific value data and an approximate analysis of pellet fuels made with raw or torrefied biomass revealed that both variants exhibited the highest net calorific value when the ratio of UBC to OPF was maintained at 70:30. As a result, a comprehensive analysis was undertaken to identify additional key properties of these for use as pellet fuels.

Ultimate analysis

Torrefied biomass in pellet fuel gave an increased carbon content (C) and a decreased oxygen content (O) from those of pellets with raw biomass. This fact seen in Table 6 can be attributed to decarboxylation and dehydration reactions, with volatilization of water and oxygen-containing compounds (González *et al.* 2021). Consequently, the carbon content was elevated, leading to a higher heating value (Tumuluru *et al.* 2016).

The nitrogen content (N) in both pellet fuel types experienced minimal changes (Fig. 9), as nitrogen in the biomass was predominantly in stable organic compounds. Most of the decomposition and nitrogen release would occur in the temperature range from 600 to 900 °C, which is far beyond the torrefaction temperature (Mei *et al.* 2015). Regarding the sulfur content (S), pellets with raw biomass exhibited lower sulfur levels than those with torrefied biomass. The sulfur content is closely associated with the ash content, which increases on torrefaction, thereby leading to elevated sulfur content. Nonetheless, both types of experimental pellet fuels demonstrated lower nitrogen and sulfur contents in comparison to lignite. Consequently, the utilization of these solid fuels, either through combustion or co-combustion with other fuels, presents the advantage of diminished (or negligible) emissions of NOx and SOx in the exhaust gases (Kongto *et al.* 2021).

Table 6. Ultimate Analyses of the Pellet Fuels

Case	Carbon content (%)	Hydrogen content (%)	Oxygen content (%)	Nitrogen content (%)	Sulfur content (%)
Non-torrefied pellet fuel	33.28	4.68	25.00	0.13	0.13
Torrefied pellet fuel	45.88	6.27	10.10	0.33	0.84

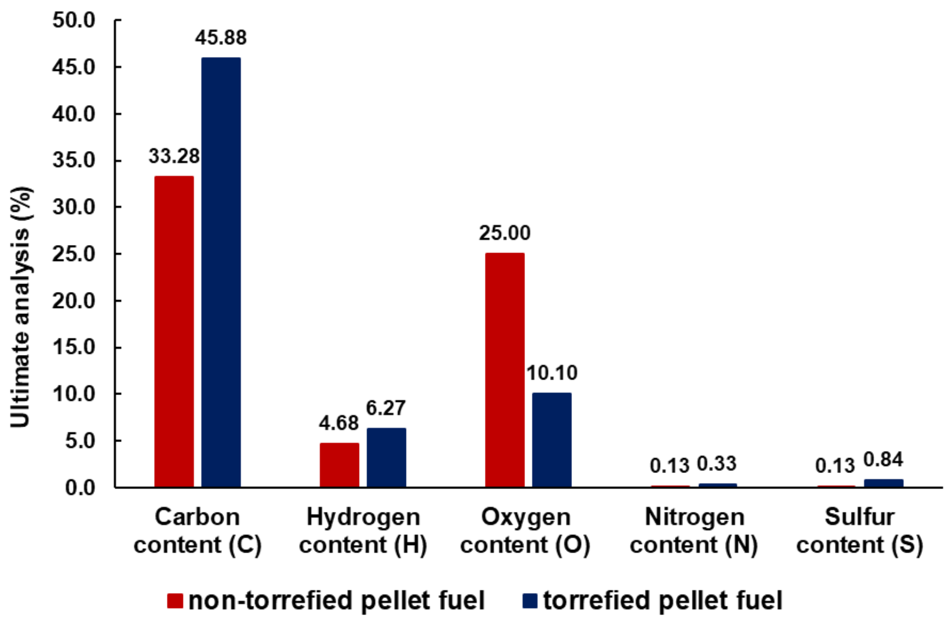

Fig. 9. Ultimate analyses of pellet fuels made with raw or torrefied biomass

Bulk density and mechanical durability

The authors assessed the bulk density and the mechanical durability of two types of pellet fuels derived by combining OPF or TOPF with UBC in a 70:30 ratio. The pellets with torrefied biomass exhibited a bulk density of 820 kg/m^3, whereas those with raw biomass had a lesser bulk density of 770 kg/m^3, as can be seen in Table 7 and Fig. 10. Bulk density is a noticeable physical property that affects various other characteristics such as water absorption, pressure resistance, and the costs of transport and storage. Consequently, it serves as a valuable indicator for comparing biomass pellets produced under different pelletizing conditions.

Mechanical durability is another critical factor to consider, as it determines the ability of pellets to withstand handling in transportation and storage. In this study, the mechanical properties of both types of pellet fuels were evaluated using the durability index at the (OPF or TOPF):UBC ratio of 70:30, giving 74.1% for pellets with raw biomass and 93.3% for pellets with torrefied biomass, as shown in Table 7. These values aligned with the respective bulk densities. However, the mechanical durability did not meet the pellet fuel standard (Refer to Standard SOLID BIOFUELS - BIOMASS PELLET and ISO/TS 1 7 2 2 5 - 8: 2 0 1 6 Solid biofuels — Fuel specifications and classes; Part 8: Graded thermally treated and densified biomass fuels) as shown in Table 7 and Fig. 11 due to the low lignin/binder content in the blend that was pelletized. For biomasses, the mechanical durability of pellets is closely linked to the presence of lignin in the final product. Pellets made from biomass with a high lignin content exhibit better adhesion and form cohesive bars. Conversely, when the raw material possesses only a low lignin content, pellet formation and adhesion are compromised, resulting in a lower density and poor durability index. These aspects can also be addressed with other types of binders, for example with starches.

Table 7. Bulk Density and Mechanical Durability Index of Pellet Fuel

Sample Type	Bulk Density (kg/m^3)	Mechanical Durability (%)	Standard of Bulk density (kg/m^3)	Standard of Mechanical durability (%)
Non-torrefied pellet fuel	770	74.1	≥ 600	≥ 97.5
Torrefied pellet fuel	820	93.3	≥ 600	≥ 96.0

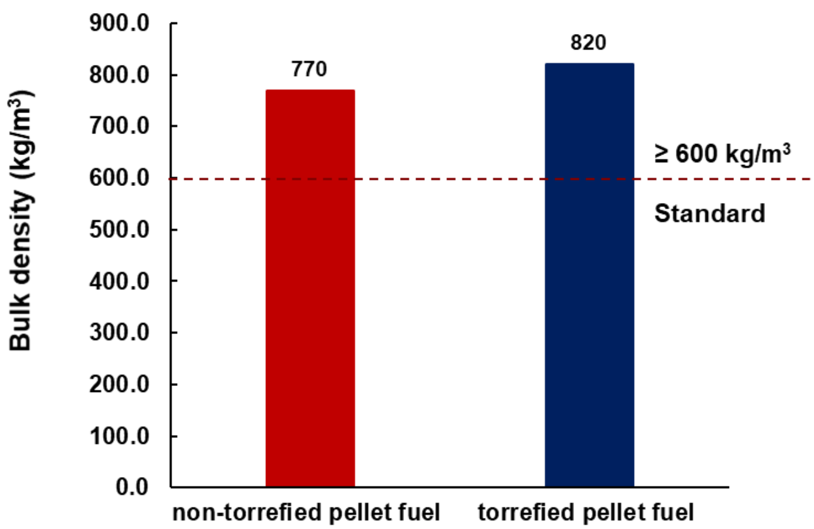

Fig. 10. Bulk density of pellet fuels made with raw or torrefied biomass

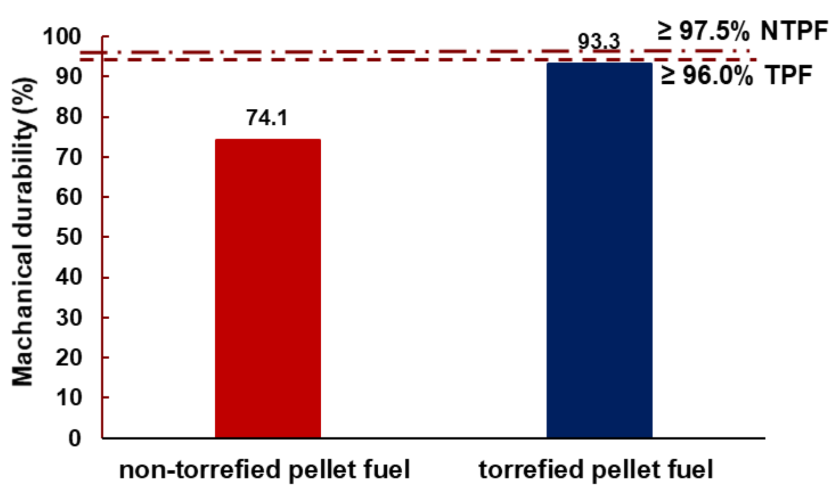

Fig. 11. Mechanical durability index of pellet fuels made with raw or torrefied biomass

TOPF exhibited a higher net calorific value (23.01 MJ/kg) compared to raw oil palm fronds (16.70 MJ/kg), indicating improved fuel performance. Its fuel ratio (0.47) approached that of coal fuels (0.5-3.0), making TOPF a viable option for combustion applications. Proximate analysis showed lower moisture and volatile matter, along with higher fixed carbon, enhancing TOPF’s combustion efficiency and energy density. These findings position TOPF as a promising and competitive alternative to conventional fuels, contributing to sustainable and cleaner energy sources.

In summary, this research demonstrates that torrefied oil palm fronds (TOPF) with enhanced heating values offer significant benefits across multiple domains. From a technical perspective, TOPF’s higher net calorific value and improved fuel ratio make it an attractive choice for solid biomass fuel applications in power generation and industrial processes, while the uniformity of TOPF-based pellets improves handling and storage properties. Economically, torrefaction presents a cost-effective means of converting agricultural waste into high-quality energy-rich pellets, reducing reliance on expensive fossil fuels and creating new market opportunities. Moreover, these findings contribute to sustainability by promoting the utilization of biomass resources, reducing carbon emissions, and supporting global sustainability goals. Torrefaction also aligns with circular economy principles, transforming agricultural waste into a valuable resource, and addressing waste management challenges through sustainable waste valorization. Overall, our research highlights the potential of TOPF in advancing cleaner and more sustainable energy production.

CONCLUSIONS

1. Torrefaction significantly increased the net calorific value of oil palm fronds (conditions: 70:30 (TOPF:UBC), 300 °C, and 40 min), reaching levels comparable to conventional coal fuels. This enhanced energy content positions TOPF as a viable alternative to fossil fuels, contributing to the promotion of renewable energy sources and reducing greenhouse gas emissions.
2. While the torrefied oil palm fronds offer enhanced fuel properties, it is essential to achieve compliance with established fuel standards, such as ISO/TS 17225-8 (2016). This study revealed that certain formulations of TOPF and used bleaching clay (UBC) failed to meet the pellet fuel standard due to low lignin/binder content in the blend. Addressing this challenge would require exploring alternative binders, such as starches, to improve mechanical durability and achieve adherence to fuel quality specifications.
3. Torrefaction provides an opportunity for valorizing agricultural waste, such as oil palm fronds, by converting them into valuable and energy-rich biomass pellets, reducing environmental burdens associated with waste disposal.
4. Finally, the use of TOPF for fuel applications contributes to diversifying energy sources and reducing dependence on fossil fuels, promoting a more sustainable energy landscape; moreover, torrefaction provides an opportunity for valorizing agricultural waste, such as oil palm fronds, by converting them into valuable and energy-rich biomass pellets, reducing environmental burdens associated with waste disposal.

ACKNOWLEDGMENTS

This work was supported by Fundamental Fund 2023 (FF2566: SIT6601238S) under reference number 23836.

Authors thank the Research and Development Office (RDO), Prince of Songkla University, Hat Yai Campus, and Prince of Songkla University, Surat Thani Campus, for supporting this project under the Integrated High Value of Oleochemical (IH-VO) Research Center. Ms. Pensiri Romyen gives thanks for her Thesis Research Grant for scientific research/development of tools/development of innovations that require materials, Engineering Graduate Scholarship.

Author Contributions

The manuscript was written through the contributions of all authors. All Authors have given their approval to the final version of the manuscript.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Article submitted: June 17, 2023; Peer review completed: July 26, 2023; Revised version received and accepted: August 13, 2023; Published: August 16, 2023.
DOI: 10.15376/biores.18.4.6986-7002