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Research Article

The characteristics and emissions of low-pressure densified torrefied elephant dung fuel briquette

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Abstract. Elephant dung is the camp's undigested fiber waste. For more effective waste management, the conversion of dung to torrefied solid and the formation of solid torrefied into fuel briquettes, as well as their properties, were investigated. The dung was improved through torrefaction at 280°C for 150 sec in a pilot-scale reactor with a feeding rate of 600 g/h. The torrefied elephant dung had 17 MJ/kg of HHV, a solid yield of 79%, and a fixed carbon content of 20%. A mixture of torrefied dung, binder, and water was compressed at 40 bars to a density of 860 kg/m^3, or 12 GJ/m^3. Their H/C and O/C atomic ratios were in the range of typical biomass. However, due to their moisture content of over 7%, the HHV of the fuel briquettes was below 17 MJ/kg. Moreover, their thermal efficiency was less than 7% due to durability issues, despite having a great fuel ratio and thermal stability. The combustion of these briquettes resulted in less than 850 ppm of CO. To improve the combustibility of this solid biofuel, it is recommended to develop a production process and a suitable stove specifically for these briquettes.

Keywords: Elephant dung; torrefaction; torrefied elephant dung; fuel briquette; undigested fiber waste, nature fiber

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1. Introduction

In Thailand, 3,500 domestic elephants (*Elephas maximus*) reside in elephant camps (Vitithumakhun *et al.* 2018), excreting about 60% of their daily food intake (Stępień *et al.* 2019; Sandhage-Hofmann *et al.* 2021; Abeysinghe *et al.* 2022) which amounts to 360 tons of wet dung each day. The issue of disposing of elephant dung has been addressed by proprietors through careless piling or burying near natural water sources (Mainkaew, Pattiya & Jansri 2023) posing a risk of water pollution and the release of unpleasant odors and hazardous gases (Abeysinghe *et al.* 2022; Mathews & Thadathil 2011). Elephant dung (ED) contains a considerable number of undigested fibers, such as 35-47% cellulose, 28-30% hemicellulose, and 15-18% lignin (Abeysinghe *et al.* 2022). As a result of this high fiber content, a significant portion of ED takes a long time to decompose naturally, with a rate of 6.4×10^{-2} kg/day (Vanleeuwe & Probert 2014). Thus, it is routinely burned throughout the dry season, generating air pollution (Mathews & Thadathil 2011; Zhang *et al.* 2022). Ineffective waste management in elephant camps has led to growing concerns among people living nearby. To address this issue, ED has been suggested as a feedstock for energy production, including biochar (Stępień *et al.* 2019), biogas (Kumer *et al.* 2022), biohydrogen (Saripan *et al.* 2022), and fuel briquettes (Mainkaew, Pattiya & Jansri 2023). These approaches can transform waste into a valuable resource, minimizing environmental impact.

A fascinating solution to the problem of managing the copious amounts of elephant dung generated in camps involves converting it into fuel briquettes, boosting their energy density (Hwangdee *et al.* 2022) and potentially increasing their value, thus replacing traditional fuels like wood and charcoal. In 2011, Mathews & Thadathil studied the use of elephant dung as solid fuel and produced fuel briquettes using shorter fibers obtained from washed elephant dung with a high heating value (HHV) of over 17 MJ/kg. Fuel briquettes had to be produced using this process over a long period of time, and much water was wasted in the process overall. However, the long production time and water wastage in this method led Mainkaew & Jansri (2020) to employ unwashed elephant dung as raw material, resulting in fuel briquettes with densities ranging from 496 kg/m^3 to 798 kg/m^3. Mainkaew, Pattiya & Jansri (2023) conducted additional optimization studies using a weight ratio of 7:3:1 for elephant dung, binder, and water, and compressing the mixture at 40 bars. The resulting fuel briquettes had a density and energy density surpassing 600 kg/m^3 and 9 GJ/m^3, respectively. However, the heating value of the briquettes was marginally lower than the results obtained by Mathews and Thadathil (2011). Therefore, improvements are still necessary to enhance the HHV of fuel briquettes produced from elephant dung.

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Thermally treating the biomass prior to briquetting is a technique that can improve the heating value of biomass fuel briquettes. It was discovered that transforming the raw material biochar was discovered to produce fuel briquettes with a higher heating value (Deshannavar *et al.* 2018). Most of the time, carbonization (Ibitoye *et al.* 2022) and torrefaction (Fuad *et al.* 2020) are used to turn biomass into biochar. Carbonization produced more HHV-containing biochar than torrefaction, which converted biomass to biochar at 300-500°C in an inert atmosphere (Ibitoye *et al.* 2022). Torrefaction, on the other hand, provided higher energy yields and increased process energy efficiency (Nobre *et al.* 2019). Torrefaction was intended to enhance the heating value of biomass, possibly to an even greater extent than coal (Fuad *et al.* 2020). Stępień *et al.* (2019) improved the properties of ED through torrefaction in a mild reaction. Torrefied elephant dung (TED) was produced from a small amount of ED in a muffle furnace at temperatures of 200°C to 300°C for 20 to 60 min. The process yielded 6 to 9 g of TED, which increased the HHV from raw material to TED by 13 MJ/kg. However, the batch process took more than 20 min due to the equipment's limited size, leading to a low mass yield that was inadequate for efficient implementation. Moreover, due to limited research on fuel briquette production and emissions caused by TED, this study aims to bridge the gap by investigating them. The study utilized TED obtained from the continuous process (Sonsupap & Pattiya 2019), which could produce TED within 5 min, and a low-pressure densification technique to produce fuel briquettes. Additionally, the study evaluated the characteristics and emissions of both TED and the fuel briquettes produced.

2. Material and methods

The investigation of torrefied elephant dung fuel briquettes (TEDB) followed the process shown in Figure 1. The procedure commenced with the preparation of ED, which was then subjected to torrefaction for improvement. Subsequently, TED

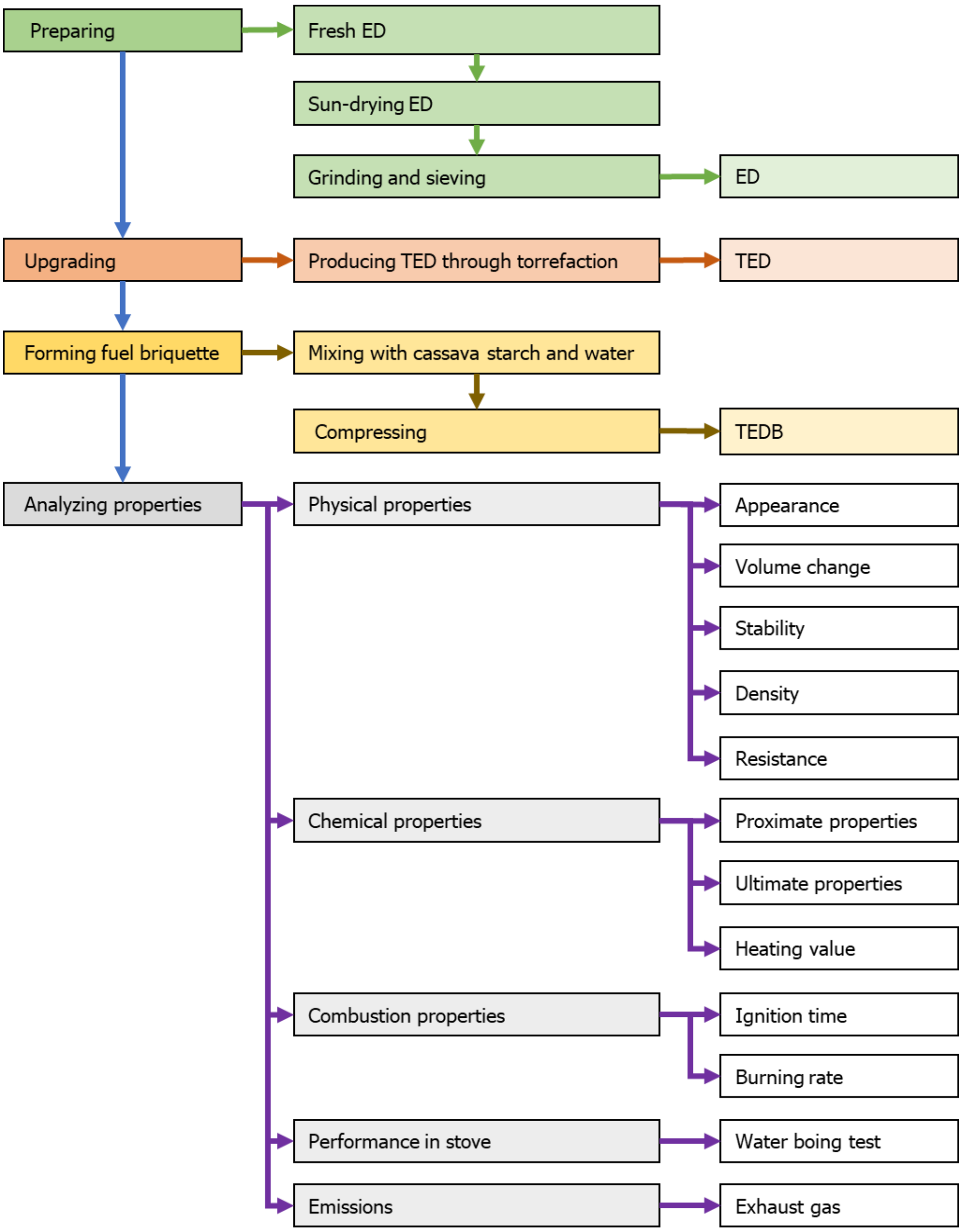

Fig 1. Schematic diagram of experiment

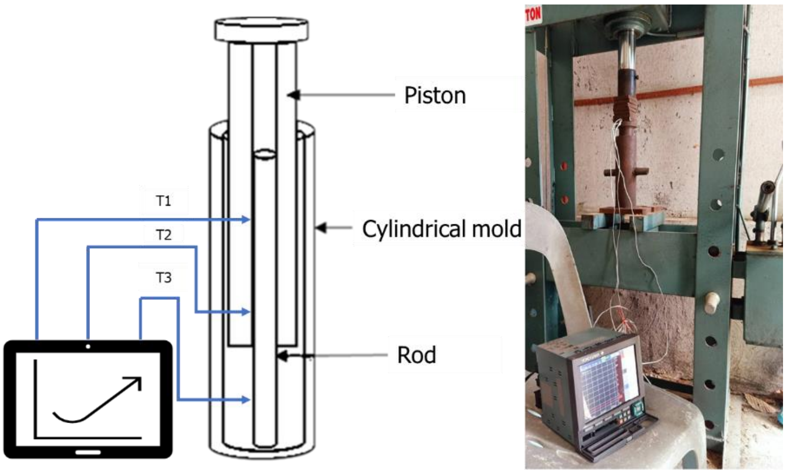

Fig 2. Temperature of fuel briquette formation monitoring

was transformed into fuel briquettes. Finally, their properties, including physical properties, chemical properties, combustion properties, performance in the stove, and emissions, were investigated.

2.1 Torrefied elephant dung

Fresh ED was sourced from an elephant camp in Kued Chang Subdistrict, Mae Tang District, Chiang Mai Province, Thailand. It was sorted manually for contaminants and sun-dried naturally for 3-5 days to reduce moisture content to below 15±1.5 wt%. The dried material was then ground and sieved to 0.841 mm (Mainkaew, Pattiya & Jansri 2023; Mainkaew & Jansri 2020). Torrefaction was performed in a vibrating continuous flow reactor (Sonsupap & Pattiya 2019) at 280°C for 150 sec with a feeding rate of 600 g/h, and TED yield (solid phase) was evaluated using Eq. 1 (Egbosiuba 2022).

$$Y = (W_{Ed}/W_{TED}) \times 100 \quad (1)$$

where Y is yield of TED (%), W_{ED} is weight of dried ED dung (g), and W_{TED} is weight of TED (g).

2.2 Torrefied elephant dung fuel briquette formation

To produce TEDB, 40 g of TED were mixed with 18.87 g of locally sourced cassava starch and 6 g of ambient temperature water. The mixture was then triple-sieved through a 0.841-mm net sieve for uniformity. The fuel briquettes were compressed to 40 bar pressure for 5 min using a cylindrical mold and a manual hydraulic press machine. During the formation of the briquette, its temperature was monitored, as shown in Figure 2. The resulting TEDBs were measured and air-dried for 5 days at room temperature in the shade (Mainkaew, Pattiya & Jansri 2023).

2.3 Characteristics and emissions of raw materials and fuel briquettes

2.3.1 Physical properties

Raw materials and fuel briquette were characterized using Scanning Electron Microscopy (SEM) for determining surface morphology using JEOL model JSM-5410 LV SEM instrument. Once the briquette was extracted from the mold and allowed to settle for a duration of 10 min, the percentage of volume change of the briquette was calculated (Aransiola *et al.* 2019). During the drying process, the dimensional stability (Jiao *et al.* 2020) and the relaxed density (Mandal *et al.* 2019) of the briquettes were evaluated while maintaining their diameter and height constant. The durability of the dried fuel briquettes was evaluated based on shatter (Adu-Poku *et al.* 2022; Ranaraja et al.,2022) and water resistance (Adu-Poku *et al.* 2022; Samomssa *et al.*, 2020). The physical properties were determined using Eqs. (2) – (6).

$$\eta_v = [(V_m - V_b)/V_m] \times 100 \quad (2)$$

where η_v is percentage of volume change (%), V_m is the volume of the cylindrical mold (cm^3) and V_b is the volume of briquette after compressing (cm^3)

$$DS = 100 - [((V_t - V_o)/V_o) \times 100] \quad (3)$$

where DS is dimensional stability (%), V_t is the volume of the briquette after release (cm^3) and V_o is the volume of the briquette after production (cm^3)

$$\rho = M/[\pi \times H \times (r_o^2 - r_i^2)] \quad (4)$$

where ρ is briquette density (kg/m^3), M is briquette mass (kg), π is mathematical constant, H is briquette height (m) and r_o and r_i are inner and outer radius of briquette (m)

$$SR = 100 - [((W_1 - W_2)/W_1) \times 100] \quad (5)$$

where SR is shatter resistance (%) and W_1 and W_2 are weight of briquette before and after shattering (cm), respectively.

$$WR = 100 - [((W_w - W_s)/W_s) \times 100] \quad (6)$$

where WR is water resistance (%), W_s is dry weight of briquette (g) and W_w is wet weight of briquette after being immersed in water (g)

2.3.2 Chemical properties

The Joint Graduate School of Energy and Environment - Central Analytical Laboratory (JGSEE - CAL), certified by the Thai Industrial Standard Institute (TISI) in accordance with TIS No.17025:2548: ISO17025:2017, analyzed the chemical properties of raw materials and fuel briquettes, including proximate and ultimate properties (Chukwuneke *et al.*, 2020). Moreover, raw materials and fuel briquettes were subjected to thermogravimetric analysis (TGA, Perkin Elmer-pyris 1, Waltham, MA, USA) under a dry nitrogen atmosphere with a scan rate 1.5°C/min in the temperature range 69-850°C to determine their thermal properties and weight loss. Based on the studies of Stępień *et al.* (2019) and Egbosiuba (2022), the fuel ratio, thermal stability, energy densification ratio, and energy yield were determined using Eqs. (7) - (10). Energy density was then calculated using Eqs. (11) - (13) according to the research of de Souza *et al.* (2022). Additionally, the H/C and O/C atomic ratios and heat capacities were evaluated (Bello *et al.*, 2021).

$$FR = FC/VM \quad (7)$$

Where FR is fuel ratio.

$$TS = FC/(FC + VM) \quad (8)$$

Where TS is thermal stability.

$$EDr = HHV_b/HHV_a \quad (9)$$

Where EDr is energy densification ratio, HHV_a is HHV of dried elephant dung (MJ/kg), and HHV_b is HHV of torrefied elephant dung (MJ/kg).

$$EY = MY \times EDr \quad (10)$$

where EY is energy yield (%) and MY is mass yield (%).

$$LHV = HHV - (0.23 \times H) \quad (11)$$

where LHV is low heating value (MJ/kg).

$$NHV = (((LHV \times 238.85) \times (1 - (0.01 \times MC))) - (6 \times MC))/238.85 \quad (12)$$

where NHV is net heating value (MJ/kg).

$$ED = NHV \times \rho \quad (13)$$

where ED is energy density (MJ/m^3).

2.3.3 Combustion properties

The method proposed by Onukak *et al.* (2017) was employed to ascertain both the ignition time and burning rate of fuel briquettes. The procedure entailed placing the fuel briquette onto a wire mesh grid and then burning it using a liquefied petroleum gas (LPG) stove. After the ignition of the stove, the duration required for the briquettes to ignite was measured and evaluated using Eq. (14). The weight of the combusted fuel briquette was recorded repeatedly until its weight stabilized. The extent of weight reduction of the briquette during a specific period was assessed using Eq. (15).

$$IT = t_1 - t_0 \quad (14)$$

where IT is ignition time (min), t_1 is time the briquette ignited (min) and t_0 is time the LPG gas stove was lit (min).

$$B_s = (Q_1 - Q_2)/t \quad (15)$$

where Bs is burning rate (g/min), Q_1 is initial weight of briquette before burning (g), Q_2 is final weight of briquette after burning (g) and t is total burning time (min).

2.3.4 Fuel briquette performance in the stove

The fuel briquettes underwent the water boiling test (WBT) through the process of boiling 500 mL of tap water on a household updraft biomass gas stove (Mainkaew, Pattiya, & Jansri 2023; Kole *et al.* 2022). Two piles of longan branches, each weighing 100 g, were used to ignite the stove, which was then left to burn for 2 min. Subsequently, 100 g of fuel briquettes were added to the stove every 5 min until the water evaporated entirely. The remaining briquettes and charcoal were then quantified, and the overall thermal efficiency and fuel consumption were computed using Eqs. (16) - (19).

$$\eta_T = [((M_w C_w) \times (T_f - T_i) + M_v L_v)/((M_F \times (1 - (1.12 \times x)) - (1.5 M_C)) \times LHV)] \times 100 \quad (16)$$

where C_w is specific heat capacity of water (kJ/kg·°C), L_v is latent heat of water vaporization (kJ/kg), LHV is low heating value (kJ/kg), M_C, M_F, M_w and M_v are the weights of remained charcoal, initial fuel, initial water, and water evaporated (kg), respectively; T_i and T_F are initial and final water temperatures (°C), respectively, and x is moisture content.

$$FCR = [(M_F \times (1 - (1.12 \times x)) - (1.5 * M_C)]/t \quad (17)$$

where FCR is fuel consumption rate (kg/min).

$$SFC = [(M_F \times (1 - (1.12 \times x)) - (1.5 * M_C)]/M_W \quad (18)$$

where SFC is specific fuel consumption (kg/kg water).

$$PC = \left[\left((M_F \times (1 - (1.12 \times x)) - (1.5 * M_C)\right) \times LHV\right]/60t \quad (19)$$

where PC is power consumption (kg/kg water).

2.3.5 Emission test

Like the WBT process, the exhaust gas released during the test was analyzed using a flue gas analyzer (Testo 350 XL – fuel gas analyzer) with a pump flow rate of around 0.87 L/min. the exhaust gas was found to comprise carbon dioxide (CO_2),

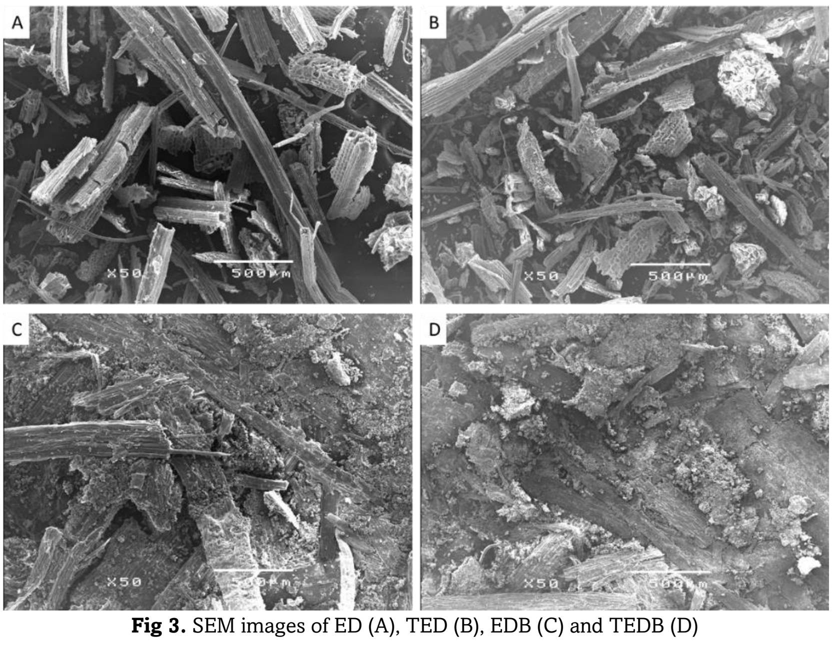

Fig 3. SEM images of ED (A), TED (B), EDB (C) and TEDB (D)

carbon monoxide (CO), nitrogen oxide (NO, and NO_x), and sulfur dioxide (SO_2).

3. Results and discussion

3.1 Torrefied elephant dung

The SEM images, shown in Figure 3, indicated that the sizes and shapes of the two dung samples differ, which could be attributed to sample preparation techniques such as grinding and sieving. ED (Figure 3A) was characterized by irregularly shaped particles with a relatively flat surface. However, the torrefaction-induced deformation of the structure led to the formation of fine particles and product porosity as shown in Figure 3B.

TED, as shown in Figure 4B, was produced with a 79% mass yield in the torrefaction process. The moisture content (MC), volatile matter (VM), and ash content (AC) of TED (Table 1) were 2.4%, 60.3%, and 19.5%, respectively, all of which were lower than the dried ED (Figure 4A). On the other hand, the fixed carbon (FC) of TED was higher than that of the raw material, at 20.2%.

The TGA results, as shown in Figure 5, revealed three distinct zones corresponding to the weight loss mechanisms of ED and TED. During the devolatilization process of the raw materials, the initial interval between 69 and 260°C at the appropriate heating rates facilitates the dehydration of moisture and the release of some volatile compounds. ED and TED weight losses were, respectively, 11 and 7 wt%. Subsequently, temperature ranges between 260 and 315°C denote zone 2. The zone is a consequence of ED and TED's initial combustion. Raw materials contained highly reactive VM (Table 1) which rapidly degraded. The effects of the heating rate on raw material weight losses were limited, with weight losses of 32 wt% for ED and 27 wt% for TED. In the final zone (315-850°C), weight loss decreased slightly. The remaining charcoal from zone 2 was further oxidized. ED and TED lost 18 and 25 wt% of their weight, respectively. Although ED and TED exhibited the same pattern of weight loss, TED's decomposition was discovered to be less than that of ED. During the process of converting ED to solid-torrefied, some of the ED compound underwent thermal decomposition, resulting in an increase in the amount of FC in TED.

TED possessed a fuel ratio of 0.33, a thermal stability of 0.25, an energy densification ratio of 1.18, and an energy yield of 93.22%. These results indicated that TED had a superior fuel ratio and thermal stability compared to ED. Although TED was more challenging to ignite and burned more slowly than ED, it maintained higher combustion temperatures and contained more unburned carbon (Egbosiuba, 2022).

TED exhibited lower levels of hydrogen (H), oxygen (O), and sulfur (S), but a higher amount of contained carbon (C) at 45.1% and nitrogen (N) at 1.4%, as shown in Table 1. TED had lower H/C and O/C atomic ratios than ED, which 1.41 and 0.80, respectively, converging more strongly towards the biomass zone, as shown in Figure 6. TED's HHV, which was 17.0 MJ/kg, exceeded that of ED. In comparison to the study by Stępień *et al.* (2019), it is evident that our study produced more TED with

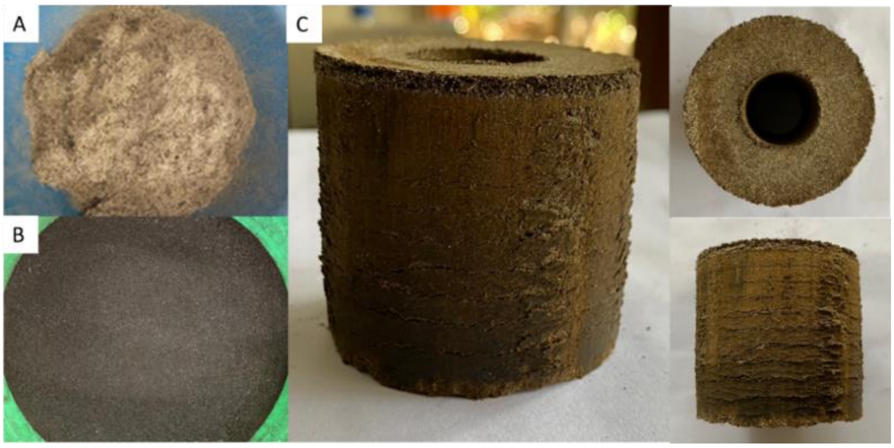

Fig 4. Raw materials [dried, ground, and sieved ED (A) and TED (B)] and TEDB (C)

Table 1
Proximate and ultimate properties of raw materials, fuel briquettes, and firewood

Properties	Unit	ED	TED	EDB	TEDB	Longan branch
Proximate properties						
MC	%	5.6	2.4	4.0	7.1	7.0
FC	%	11.6	20.2	17.8	19.2	21.9
VM	%	61.7	60.3	73.3	67.6	75.5
AC	%	26.7	19.5	8.9	13.2	2.6
HHV	MJ/kg	14.1	17.0	17.0	16.7	18.9
LHV	MJ/kg	12.6	15.7	15.6	15.1	17.4
Ultimate properties						
H	%	5.6	5.3	6.3	6.4	6.6
C	%	37.9	45.1	42.7	45.1	47.9
O	%	54.9	48	50.1	45.3	44.7
N	%	1.3	1.4	0.7	3.0	0.6
S	%	0.3	0.2	0.2	0.2	0.2
Reference		(Mainkaew *et al.* 2023)	This study	(Mainkaew *et al.* 2023)	This study	(Mainkaew *et al.* 2023)

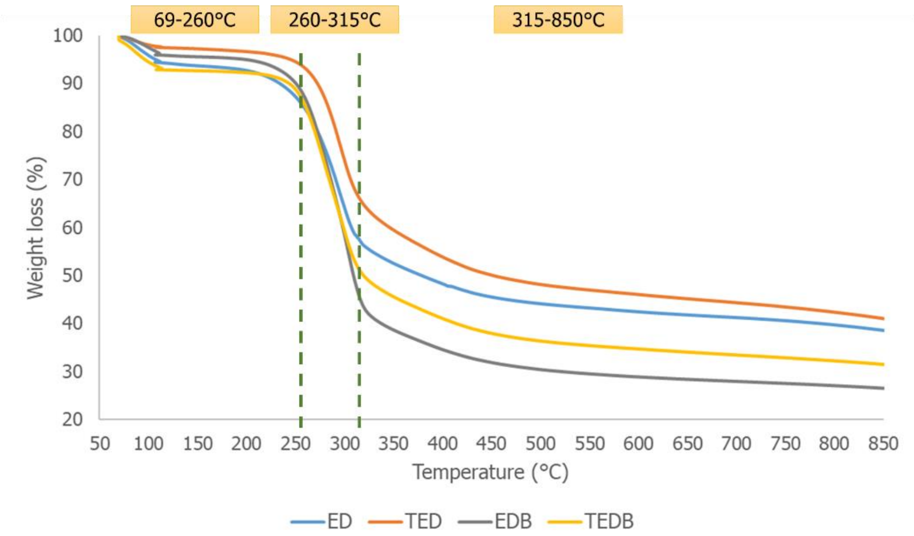

Fig 5. Thermogravimetric analysis curves of ED, TED, EDB, and TEDB

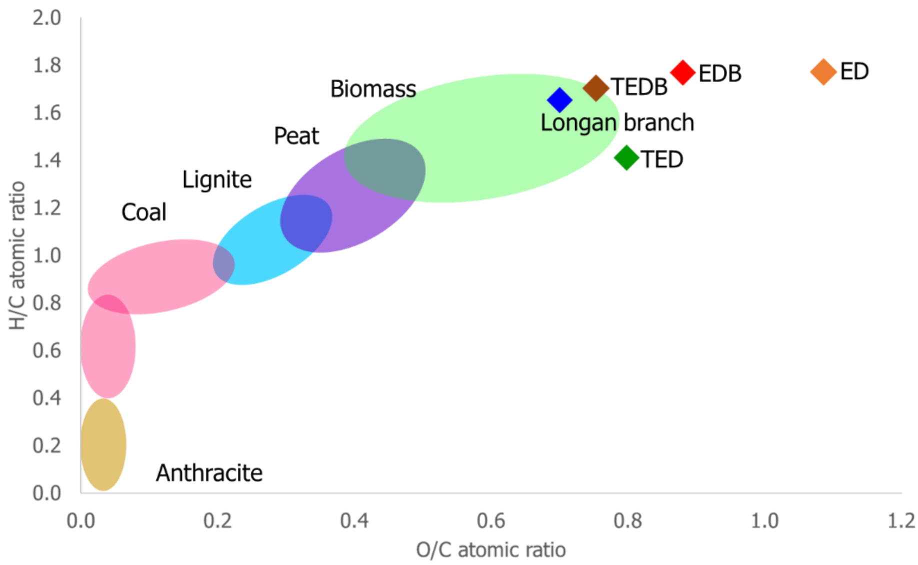

Fig 6. Van-Krevelen diagram for considered raw materials, fuel briquettes, and firewood

the lower AC but the larger MC at the same reaction temperature, albeit with a different reaction period. Although this study's processed ED had a higher MC than that reported by Stępień *et al.* (2019), its lower AC resulted in a better energy densification ratio and yield.

3.2 Torrefied elephant dung fuel briquette

The temperature variation during TEDB formation was observed to be within a limited range of 34.5-36.3°C, as shown in Figure 7. The temperature changes during the fuel briquette formation process were analyzed. In the initial period, it was noted that T1 had higher temperature than T2 and T3, primarily due to an exothermic reaction resulting from an increase in pressure. As the pressure continued to rise to meet the requirement, the temperature of T3 initially decreased and then returned to its original position. This behavior indicated that the formation of fuel briquette relied on external heat for an endothermic reaction.

After a certain period, the temperature trends of T1 and T2 became similar to that of T3, suggesting that the heat supply in T3 was insufficient for the formation process. Consequently, the formation of the fuel briquette required heat from both T1 and T2 sources. Once the required pressure was reached, the fuel briquette was compressed and held at that pressure. During this stage, it was observed that T3 exhibited heat accumulation without any significant thermal change.

Subsequently, the pressure was reduced by withdrawing the hydraulic punch. Initially, the heat in T3 remained constant, but over time, the heat transferred to T1 and T2. As a result, the temperature of T3 decreased, leading to shrinkage of the steel rod. Finally, the fuel briquette could be removed from the rod. Due to insufficiency heat applied to the fuel briquette formation, some properties were adversely affected. Therefore, the efficiency of fuel briquette formation could be improved by increasing the heat during the pressure increasing stage.

3.2.1 Physical properties

TEDB, as shown in Figure 4C, had a sturdy, durable, compact, and rough exterior composition. The SEM image of TEDB (Figure 3D) revealed that the cassava starch clumped and did not disperse on the surface of TED, in contrast to the unprocessed ED, as shown in Figure 3C. These factors resulted in TEDB having inferior physical properties compared to the elephant dung fuel briquette (EDB), as shown in Table 2.

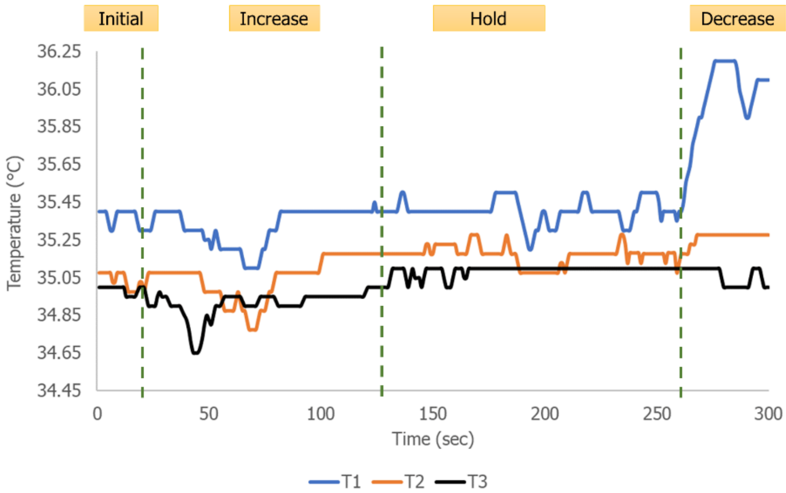

Fig 7. Temperature characteristic during fuel briquette formation

Table 2
Physical properties of fuel briquette

Physical properties	Unit	EDB	TEDB
Volume change	%	78	79
Dimensional stability	%	98	95
Relaxing density	kg/m^3	613	860
Energy density	GJ/m^3	9.1	11.9
Shatter resistance	%	79	53
Water resistance	%	39	31
Reference		(Mainkaew *et al.* 2023)	This study

Therefore, the technique for transforming TED into fuel briquettes should be modified to enhance the properties of the fuel briquettes, such as increasing the temperature during the pressure increase stage.

The percentage of volume change of TEDB following compression, as shown in Table 2, was 79%, equivalent to that of EDB. However, the dried TEDB exhibited marginally lesser dimensional stability than EDB at 95%. A significant amount of pressure was required to attain the noteworthy percentage change in fuel briquette volume and uphold dimensional stability, which constrained the raw material's adaptability (Guo *et al.* 2020). Despite this constraint, the relaxed density of TEDB was 860 kg/m^3, surpassing EDB's density of 613 kg/m^3. This density fell within the acceptable range of 600 kg/m^3 to 1,300 kg/m^3 for fuel briquette (Ramírez-Ramírez *et al.* 2022).

The shatter resistance of TEDB was found to be 53%, lower than that of EDB, and within the range considered acceptable for poor durability (defined as shatter resistance < 70%) according to ASABE Standard S269.4 (2003) (Mohd-Faizal, Mohd-Shaid, & Ahmad-Zaini 2022). The inferior shatter resistance of TEDB may be attributed to the thermal elimination of specific elements in ED that improve the bond between the raw material and binder during torrefaction. Moreover, the high moisture content of TEDB compared to EDB (Ramírez-Ramírez *et al.* 2022) may have impacted the durability of the fuel briquettes. TEDB exhibited a water resistance of less than 30% in 9 sec, indicating slower water absorption compared to EDB due to the torrefaction process. However, TEDB's water resistance was still insufficient. Therefore, improvements in the production process may be necessary to enhance both shatter and water resistance in the future.

3.2.2 Chemical properties

3.2.2.1 The proximate properties

According to Table 1, TEDB had a higher MC than the raw materials, EDB, and longan branch, but it still remained within the acceptable range for fuel briquettes, which is between 8% and 12% (Kebede, Berhe & Zergaw 2022). This finding complied with the German standard DIN 51731 (Ivashchuk *et al.* 2022), the European standard EN ISO 17225 (Kofman 2016), and the Thai Community Product Standard (Thai Industrial Standards Institute 2004). The FC of TEDB was greater than that of EDB due to the torrefaction process prior to fuel briquette production. However, TEDB had a lower FC than TED because of its higher MC. TEDB also had a higher VM than the raw materials, but lower than that of EDB and longan branch. The use of cassava starch as a binder may have contributed to the higher VM of fuel briquettes. This could result in increased smoke emissions during combustion (Wahyuni *et al.* 2022). The AC of the TEDB was found to be greater than that of EDB and longan branch, but less than that of raw materials. However, its AC of 13.2% was significantly higher than the recommendation of Kebede, Berhe & Zergaw (2022). Moreover, it failed to meet the requirements of both the German standard DIN 51731 (Ivashchuk *et al.* 2022) and the European standard EN ISO 17225 (Kofman 2016), resulting in more inorganic waste during combustion (Ramírez-Ramírez *et al.* 2022).

The weight-to-temperature loss of EDB and TEDB, as shown in Figure 5, follows the same pattern as the weight loss of ED and TED. The TGA results indicated that the initial zone had a 10 wt% weight loss for both EDB and TEDB, which were comparable to that of the ED. In zone 2, EDB and TEDB lost 45 and 39 wt% of their weight, respectively, which was greater than the ED and TED. The reason for this difference was the use of cassava starch as the binder. Not only did the reaction in zone 2 result in a rapid decrease in raw material weight, but the binder also had a significant effect on VM of the fuel briquettes (Table 1). In the final zone, EDB and TEDB lost 19 and 20 wt% of their weight, respectively. The combustion reaction in zone 2 was rapid and resulted in a greater weight loss, leaving a smaller quantity of charcoal available for the reaction in zone 3 compared to ED and TED. However, their decompositions were comparable to that of ED but inferior to that of TED.

TEDB exhibited a fuel ratio of 0.28 and a thermal stability of 0.22. Its fuel ratio and thermal stability were lower than those of TED, as cassava starch was used as a binder. However, its fuel ratio and thermal stability were better than EDB and comparable to longan branch. The combustion efficiency of TEDB might be superior to EDB and equivalent to that of the longan branch (Egbosiuba 2022).

3.2.2.2 Ultimate properties

The ultimate properties of TEDB, as shown in Table 1, revealed that it had a higher concentration of H than EDB and raw materials, with the exception of the longan branch. However, its O concentration was lower than the others. While TEDB's C concentration was similar to that of TED, it was greater than that of ED and EDB and lower than that of the longan branch. TEDB exhibited the highest N concentration, and its S concentration was 0.2%, the same as all others except for ED. However, TEDB failed to meet the European standard EN ISO 17225 (Kofman 2016) for N and S concentrations.

TED had H/C and O/C atomic ratios of 1.70 and 0.75, respectively. The fuel briquette had a higher H/C atomic ratio than TED and the longan branch but a lower ratio than ED and EDB. It also had a lower O/C ratio, except for the longan branch. Only TEDB reached the boundary of the biomass zone on the Van-Krevelen diagram (Jenkins, 1998), as shown in Figure 6, indicating that densification and ED processing had an impact on the relationship between H/C and O/C atomic ratios. TED and EDB split from ED and converged into the biomass zone. Despite TEDB's H/C and O/C atomic ratios being in the biomass zone, its HHV was lower than that of the longan branch. Additionally, while EDB's H/C and O/C atomic ratio relationships were outside of the biomass zone, TEDB's HHV was still lower despite being derived from TED and employing the cassava starch equivalent binder. Furthermore, the HHV of TEDB was lower than that of TED, possibly due to its higher MC and the use of cassava starch as a binder.

3.2.2.3 Heating value properties

Torrefaction enhanced the properties of the raw material used for fuel briquettes, resulting in a remarkable energy density of 11.9 GJ/m^3 (Table 2), surpassing that of EDB. However, TEDB had a lower HHV of 16.7 MJ/kg than TED, EDB, and longan branch, as shown in Table 1, due to its higher moisture content. This value was lower than the 17.5 MJ/kg HHV reported by Mathews & Thadathil (2011). Moreover, this value was below the minimum energy content of 20.9 MJ/kg specified by the Thai Community Product Standard (Thai Industrial Standards Institute 2004). Combusting TEDB necessitated more energy to evaporate the excess moisture, which lowered the heating value and ignition of the fuel briquettes (Kofman 2016), even though the MC met the requirements. Drying the TEDB as much as possible could raise the HHV, despite torrefaction improving the ED. Additionally, the quantity of binder used had an impact on the HHV of fuel briquettes (Deshannavar *et al.* 2018; Mohd-Faizal, Mohd-Shaid, & Ahmad-Zaini 2022).

Based on a comparison, 1 kg of TEDB was able to replace 0.98 kg of EDB (Mainkaew, Pattiya, & Jansri 2023), 0.89 kg of longan branch (Mainkaew, Pattiya, & Jansri 2023), 0.65 kg of charcoal (25.70 MJ/kg) (Otieno *et al.* 2022), and 0.33 kg of LPG (50.15 MJ/kg) (Essom Co., LTD. 2014). In order to enhance the substitution ratio, it is recommended to explore options such as producing fuel briquettes without a binder or replacing water with alternative liquids or volatile solvents (Mohd-Faizal, Mohd-Shaid, & Ahmad-Zaini 2022).

3.2.3 Combustion properties

According to the studies conducted by Nurhayati, Naufal & Hariadi (2022), Vershinina *et al.* (2022), Nikiema *et al.* (2022), and Inegbedion & Erameh (2023), the ignition time and combustion rate of TEDB should be reduced due to the high density and abundance of AC raw material. In practice, TEDB ignited in 90 sec, which was faster than EDB's approximate ignition time of 120 sec (Mainkaew, Pattiya, & Jansri 2023). Moreover, TEDB's combustion rate was 1 g/min, lower than the 0.6 g/min achieved with EDB (Mainkaew, Pattiya, & Jansri 2023). The TEDB ignition time and combustion rate were inconsistent with the fuel ratio and thermal stability, likely due to inadequate shatter resistance and water resistance. Poor combustion properties may result from weak bonds between TED and the binder, as observed in the physical properties of TEDB.

3.2.4 Performance of the fuel briquette in the stove

Compared to EDB and longan branch (Mainkaew, Pattiya, & Jansri 2023), 1.56 of TEDB required 47 min to boil 500 mL of water, which was 22 min longer and consumed 0.69 kg and 0.36 kg more fuel, respectively. TEDB improved the overall thermal efficiency of the household updraft biomass gas stove by 6.1%, as shown in Table 3. It was significantly lower than the efficiency improvements achieved by other fuels. Moreover, TEDB showed significantly greater FCR, SFC, and PC values than the EDB and longan branch at 0.029 kg/min, 2.7 kg/kg, and 7.4 kW, respectively. These findings supported the previously discussed issue of combustion properties. Improvements in TEDB production for enhancing fuel briquette performance in stoves, as well as the use of TEDB in conjunction with suitable stoves, may be beneficial.

3.2.4 Emission properties

Table 3
Thermal properties of fuel briquette and firewood

Properties	Unit	EDB	TEDB	longan branch
Overall thermal efficiency	%	21.8	6.1	17.1
FCR	kg/min	0.015	0.029	0.017
SFC	kg/kg	0.8	2.7	0.9
PC	kW	3.9	7.4	5.0
Reference		(Mainkaew *et al.* 2023)	This study	(Mainkaew *et al.* 2023)

Table 4
Emissions of fuel briquette and firewood

Properties	Unit	EDB	TEDB	longan branch	Thai general ambient air quality standard (1 h)	Thai polluted air from industrial factory standard
CO_2	ppm	5.5×10^4	3.5×10^4	5.2×10^4	N/A	N/A
CO	ppm	2.1×10^3	8.4×10^2	4.9×10^2	30	690
NO_2	ppm	1.0×10^2	82.9	94.2	0.17	200
NO_x	ppm	1.1×10^2	87.1	98.9	N/A	N/A
SO_2	ppm	0.0	0.0	0.0	0.30	60
Reference		(Mainkaew *et al.* 2023)	This study	(Mainkaew *et al.* 2023)	(Announcement of the National Environment Board 1995; 2001)	(Announcement of Ministry of Natural Resources and Environment 2006)

During combustion, TEDB emitted lower levels of CO_2 (3.5×10^4 ppm) than EDB and longan branch (Mainkaew, Pattiya, & Jansri 2023), as shown in Table 4. While its CO concentration was 8.4×10^2 ppm, higher than longan branch but lower than EDB. The carbon content of the fuel briquettes, the temperature generated by the stove, and oxidizing agent quantity all caused the CO_2 concentration to be over 40 times higher than the CO concentration (Vershinina *et al.* 2022). Although TEDB had a higher N concentration than EDB and longan branch (Table 1), its NO_2 and NO_x emissions were lower, as shown in Table 4. TEDB did not meet the European standard EN ISO 17225 for S content (Kofman 2016), but SO_2 emission (Table 4) was undetectable.

The CO emission from TEDB combustion did not meet the general ambient air quality standard defined by the National Environment Board Notification, Thailand (Announcement of the National Environment Board 1995; 2001), and the polluted air from industrial factory standard defined by the Ministry of Natural Resources and Environment, Thailand (Announcement of Ministry of Natural Resources and Environment 2006). However, the SO_2 emission complied with both standards. Additionally, the NO_2 emission from TEDB was significantly lower than that required by the later standard.

Although fuel briquette emissions only meet a few standard parameters, a comparison between TEDB and EDB revealed that the former had lower emissions. This is because more FC was obtained during the conversion of ED to TED through the torrefaction process, as shown in Table 1. The use of cassava starch as the binder in the fuel briquette formation led to a decrease in FC and an increase in VM. Nonetheless, TEDB's FC and VM were still inferior to EDB. When TEDB was utilized in household biomass gas stove, the modest quantity of producer gas generated by the first stage of the stove could be combusted more efficiently in the second stage than EDB. As a result, the emissions induced by the combustion of TEDB were substantially less than those of EDB. However, TEDB should be used in a well-ventilated area for indoor applications.

4. Conclusion

Through torrefaction, the proximal properties, ultimate properties, and heating value of ED can be improved. TED achieved a yield of 79%, with FC exceeding 20%. It had an HHV of 17 MJ/kg, compared to 14 MJ/kg in dried ED. TED, binder, and water were then compressed at 40 bars in a 7:3:1 weight ratio to form fuel briquettes, resulting in TEDB with a density greater than 850 kg/m^3 and an energy density greater than 11 GJ/m^3. However, TEDB's moisture content was over 7%, leading to an HHV of less than 17 MJ/kg. Despite having a higher fuel ratio and greater thermal stability than EDB, at 0.28 and 0.22, respectively, TEDB had limited durability due to poor bonding strength between TED and the binder, resulting in shatter resistance and water resistance less than 55% and 40%, respectively. TED exhibited greater physical and thermal properties. When TED was formed into fuel briquettes using the same approach as EDB, its properties were diminished. It was found that the process was not suitable for producing TEDB because raw materials for fuel briquettes had different characteristics. If the goal was to continue as before, increasing the temperature during the formation of fuel briquettes could be helpful since the endothermic reaction occurred during compression. Additionally, to upgrade ED to a fuel that could replace coal, its chemical properties must be altered by increasing the C content or decreasing the H and O content through appropriate thermal treatment and its density must be increased.

The briquette properties led to an overall thermal efficiency of less than 7%, with FCR, SFC, and PC exceeding 0.025 kg/min, 2.5 kg/kg, and 7 kW, respectively. When used as a cooking fuel, TEDB emitted a greater CO_2/CO mass ratio (> 40 times) than EDB, but less NO_2 (82.9 ppm) and NO_x (87.1 ppm), with all emissions being comparable to SO_2 (0 ppm). Using TEDB as a fuel increased the efficiency of combustion. Nonetheless, it is essential to use a suitable stove to enhance its performance.

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Competing interest

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CRediT authorship contribution statement

Artidtaya Mainkaew: Writing – original draft & review, Methodology; Sommas Kaewluan: Methodology; Adisak Pattiya: Conceptualization, Writing – editing, Research summaries and recommendation; Surachai Narrat Jansri: Conceptualization, Writing – original draft & review, Methodology, Writing – editing, Research summaries and recommendation

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