Combustion kinetics of char product derived from torrefaction of Miscanthus pellets with different operational conditions

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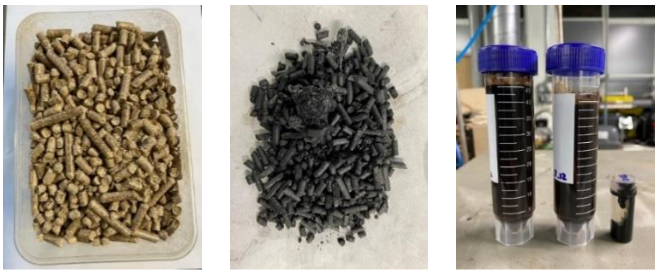
Biomass, as a biofuel for generating electricity and heating, has became more prominent over the last 3 decades, with 471,000 GWh and 620,192 TJ generated worldwide in 2020 (IEA, 2023). Biomass should be considered as a preferable energy source as it not only has a secure and stable supply, but it also produces cleaner energy compared to fossil fuels. However, biomass has high reactivity that could be a disadvantage for energy generation purposes as it is particularly volatile and needs to be handled cautiously. To improve biomass properties, particularly its combustion behaviour, torrefaction can be used as a thermal pre-treatment to make the biomass product less reactive, with a lower volatile content that increase ignition temperature. This study aims to examine the combustion behaviour and kinetic properties of torrified Miscanthus pellets derived from a torrification process conducted with different temperatures and pellets sizes. The combustion characteristics of biomass were examined using Thermogravimetric Analysis (TGA) and Derivative Thermogravimetry (DTG) data to investigate the thermal behavior and decomposition kinetics of biomass (Chen, et al., 2020). The activation energy was also calculated as kinetic analysis is a crucial step in designing and optimizing thermal systems, particularly for use on an industrial scale (Zhang, et al., 2020).

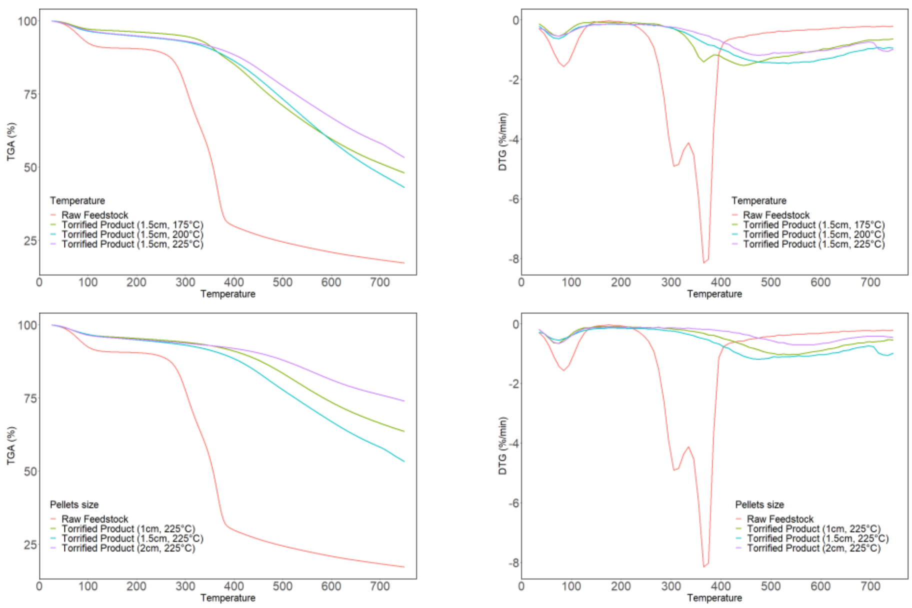
The torrefaction experiments were carried out using a 1.9 litre reactor, with a heating tape as a heat source. For each experiment, 400g of Miscanthus pellets was placed inside the reactor at different temperatures (175, 200, and 225°C) and with varying pellets sizes (1, 1.5, and 2cm). The raw Miscanthus pellets and char products were analysed using a Thermal Analyser (PerkinElmer TGA 4000, Perkin Elmer, United Kingdom) to identify the combustion characteristics and to evaluate the kinetic parameter, particularly the activation energy. The samples were heated using conditioned atmospheric air from 25 to 750°C, at a heating rate of 10, 15, and 20°C per minute. The combustion characteristics observed were the ignition, peak, and burnout temperature, derived from TGA and DTG graphs. The ignition temperature happens when the fuel either starts burning or suffers a sudden mass loss, the peak temperature occurrs when maximum mass loss happens, and the burnout temperature happens when the combustion rate decreases to 1°C/min (Ro, et al., 2019). In this study, activation energy was calculated using the isoconversional model free approach: Kissinger-Akahira-Sonuse (KAS) method.



(a) (b) (c)

Figure 1. (a) Raw Miscanthus pellets, (b) Char and (c) Liquid Product after Torrefaction at 225°C

Each experiment produced black solid char product and brown aqueous product. This study was focused on the analysis of the char product and its combustion kinetics which can be explained by TGA and DTG graphs on Figure 2 and detailed combustion characteristics on Table 1. The TGA graphs showed the mass retained from the char products were about 50%, which were greater than from raw Miscanthus pellets, due to the removal of volatile matter and the increase of ash content from the torrefaction process. On the other hand, the DTG graph used to observe sample reactivity as the higher peak on the DTG graphs indicate the sample is more reactive which leads to a lower thermal efficiency and more released pollutants (Krysanova, et al., 2022). Char product has lower DTG peak than raw feedstock which means the torrefaction produced less reactive solid product, which started to burn and finally completely burned at higher temperatures. Torrefaction with temperature of 225°C, regardless of the pellets sizes, yielded char with high ignition temperature which are above 373°C. While the torrified product of feedstock with 2cm pellets length has a higher ignition and burnout temperature than coal, which are 398.96 and 635°C, respectively. The larger particle size is the main cause of slowing the combustion process.



(a) (b)

Figure 2. (a) TGA graphs and (b) DTG graphs of raw miscanthus pellets and torrified miscanthus pellets

Activation energy (Eα) is a key characteristic of fuel, often referred to as the energy barrier or minimum energy required for the molecule to reach the activation state (kJ/mol) (Hu, et al., 2020). Char products have a higher activation energy than raw feedstock (Table 1) which indicates that they are in a stable state, therefore they require more energy to make molecules react. The ignition and peak temperatures of char products are also higher than raw feedstock, pointing to a lower volatility. Regarding pellets sizes, pellets with a 1cm length have higher activation energy at 183.53 kJ/mol, compared to pellets with 1.5 and 2cm length with lower values at 133.42 kJ/mol and 159.01 kJ/mol.

Table 1. Combustion Characteristics and Kinetic Parameter of Samples

Samples	**T (°C)**	**L (cm)**	**T_v (°C)**	**T_i (°C)**	**T_p (°C)**	**T_b (°C)**	**Eα (kJ/mol)**
Raw feedstock	-	-	175	299.47	365	398.33	84.40
Torrified product	175	1.5	150	342.33	450	563.5	118.85
	200	1.5	178.33	366.53	508.33	599.33	200.05
	225	1.5	178.33	376.95	505	560	133.42
	225	1	171.67	392.25	548.33	617.33	183.53
	225	2	188.33	398.96	575	635	159.01
Coal (Ro, 2018)	-	-	-	373	515	623	-

Notes: T = temperature, L = pellets length, T_v = devolatilisation temperature, Ti = ignition temperature, T_p = peak temperature, T_b = burnout temperature, Eα = activation energy

Torrefaction produced char products with better combustion characteristics, with lower reactivity and volatility. The ignition temperature of char derived from torrefaction at 225°C is higher than ignition temperature of coal, the char started to burn around temperatures of 376 – 398°C. The less reactive products are also indications of better fuel properties that result in better thermal efficiency and release less pollutants when used as biofuel. The less reactive product also has a higher overall activation energy.

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