# Emissions and Combustion Characteristics of Torrefied Wood Pellets

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The influence of torrefaction temperature on the durability, combustion characteristics, and emissions of CO, $CO_2$, NOX, and particulate matter (PM) from biomass pellets was studied. The pellets were torrefied under inert conditions at 225, 250, and 300 °C for 60 min. Physical properties, such as weight loss, fines percentage, pellet durability index (PDI), and water absorption, were evaluated using ISO standards. The weight loss increased with higher torrefaction temperatures. Torrefied pellets had lower water absorption than untreated pellets. Fines percentage increased with torrefaction temperature while PDI decreased. Torrefied pellets at 300 °C had the lowest PDI (82.7%), while 225 °C had the highest (98.0%). The energy density and heating values increased with torrefaction temperature from 22.0 MJ/kg at 225 °C to 29.9 MJ/kg at 300 °C compared to 18.9 MJ/kg for untorrefied pellets. There were reductions in CO, $CO_2$, and NOX emissions with an increase in torrefaction temperature while PM slightly reduced. This study found that torrefied biomass pellets had lower $CO_2$ emissions than raw pellets.

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## INTRODUCTION

In recent decades, the global energy demand has been on a steady rise, leading to an increase in greenhouse gas emissions (Maxwell *et al*. 2020; Saletnik *et al*. 2022). As a result, the focus has shifted toward low-carbon renewable energy sources as a preferred alternative to fossil fuels (Singh *et al.* 2016). Among these, biomass pellets have been identified as a sustainable fuel source for domestic heating and electricity cogeneration due to their low NOX, low $SO_2$, and carbon neutrality (Sarker *et al*. 2020). Biomass pellets are in high demand in several European countries due to the supporting legislation advocating the use of renewable energy in these countries (Pantaleo 2020). Thus, torrefied biomass pellets are gaining traction in the energy mix because of their high energy concentration (Saletnik *et al*. 2022; Sarker *et al*. 2022), long-term storage capabilities, and ease of overseas transportation (Nunes *et al*. 2020). Therefore, there is a growing interest in using torrefied wood for domestic use and gasification.

Torrefied pellets are biofuel produced through a thermochemical process that takes place at temperatures between 200 to 300 ℃ in the absence of oxygen (Yoshida *et al.* 2015; Parker *et al*. 2020; Wang *et al*. 2020). This process improves biomass' carbon content, higher heating value, and hydrophobicity and reduces its mass by 20% to 30% (Zheng *et* *al*. 2013; Cambero *et al*. 2015; Singh *et al*. 2020). The process also removes moisture and some volatile matter, thus enhancing the pellets' quality. The torrefied pellets also have higher ignition temperature than raw pellets. Riaz *et al*. (2023) reported that the ignition temperature of torrefied pellets was 346.2 °C, compared to 298.2 °C for raw pellets. This means that torrefied pellets need to be heated to a higher temperature before they start to burn because the torrefaction process removed some of the volatile components from the biomass and increased the density of the pellets. Thus, higher temperature is required to ignite torrefied pellets compared with raw pellets. The higher ignition temperature of torrefied pellets means that torrefied pellets burn more slowly and evenly than raw pellets, which can lead to a more efficient combustion process.

Torrefaction can be applied to biomass raw materials or finished pellets (Bridgeman *et al.* 2010; Sarker *et al*. 2021), and it has been shown to reduce the production of smoke during combustion. According to Arous *et al*. (2021), when wood material is exposed to high temperatures, it undergoes a transformation that increases its carbon content while reducing moisture, thus improving subsequent combustion efficiency. Consequently, the O/C ratio significantly decreases, leading to a higher heating value (Wang *et al*. 2020).

Torrefied wood pellets exhibit environmentally friendly performance compared to coal, firewood, and natural, conventional biomass pellets (Zhang *et al.* 2020). This is due to the reduced fossil carbon emission and greenhouse gas emissions (Maxwell *et al*. 2020). It has also been reported that biomass properties are thermally modified when exposed to mild pyrolysis temperatures of 200 to 280 °C under an inert atmosphere (Alizadeh *et al.* 2022). The hemicellulose content is thermally decomposed at 280 °C with lower benzopyrene content, lower alkali metal, and lower chlorine (Chen *et al.* 2018; Wang *et al.* 2020; Park *et al.* 2020) and moisture content compared to raw biomass feedstock (Mitchel 2016). At temperatures between 260 and 280 °C, the biomass' elemental hydrogen and oxygen content decreased while the carbon content increased. The reduction in oxygen and hydrogen mitigated the production of smoke during combustion.

Torrefied wood has been reported to emit fewer pollutants compared to raw wood (Atiku 2015; Maxwell *et al.* 2020), thus reducing GHG pollution due to the combustion of natural wood, which produces fine particles, and soot that can have adverse health effects (Yoshida *et al.* 2021). Previous studies on the nature and effects of fine particulate emissions from wood combustion (Atiku *et al.* 2015; Maxwell *et al.* 2020) indicated that the decomposition products of wood pyrolysis, such as furfural contributed to the formation of fine carbonaceous matters, while other studies confirmed that the production of eugenol increased the rate of soot formation (Zhang *et al.* 2020; Sarker *et al.* 2021). However, there is limited information on the effects of torrefaction on the particulate emissions during the combustion of thermally modified pellets.

The aim of this study was to investigate the combustion properties and emissions from torrefied pellets, focusing on the impact of torrefaction temperature on the combustion properties, and CO, $CO_2$, NOX, and particulate emissions. The findings will inform the development of cleaner and more efficient bioenergy sources and reduce global greenhouse gas emissions.

## EXPERIMENTAL

### Materials and Methods

The pelletized materials used for this study were sourced from a pellet company in New Brunswick, Canada. The pellets were produced from spruce wood, softwood sawdust shavings, and other wood particles. The pellets were torrefied under an inert atmospheric condition chamber at 225, 250, and 300 °C for 60 min retention time. The torrefied pellets were characterized for physical properties: weight loss, percentage of fines, pellet durability index, and hygroscopicity. The combustion properties and emissions of the pellets during combustion were also determined according to ISO standard test methods. For each experiment, the samples were replicated five times. The experiments were carried out at the Canadian BioEnergy Centre, a division of the Wood Science and Technology Centre, Hugh John Flemming Forestry Centre, 1350 Regent Street, Fredericton, NB, Canada.

## Determination of Physical Properties of the Pellets

### *Determination of weight loss*

The weight loss was determined by calculating the difference in weights due to torrefaction according to the procedure described in Annex A of ISO 17225-8 (2016). Samples of 500 g of pellets were dried to constant weight and torrefied at 225, 250, and 300 °C for 60 min retention time, respectively. The samples were weighed before and after the torrefaction process. The percentage weight loss was calculated using Eq. 1,

$$\%\ \text{Weight loss} = \frac{(W_{TP} - W_{UTP})}{W_{UTP}} \times 100 \tag{1}$$

where $W_{\mathrm{TP}}$ is the weight of torrefied pellets (g) and $W_{\mathrm{UTP}}$ is the weight of pellets before torrefaction (g).

### *Water absorption*

Water absorption tests were conducted by immersing separately weighed samples of pellets in water for 24 h. The quantity of water absorbed by the pellets were determined and expressed as the percentage water absorption according to ISO 17831-1 (2015) standard method for determining water absorption by wood pellets.

## Determination of Pellets Durability Index (PDI) and % Fines

The PDI was determined according to ISO 17831-1 (2015) standard using the tumbling box method. The torrefied and untorrefied pellets samples were randomly selected and conditioned at 20 °C and 65% humidity for 48 h to achieve a constant moisture content. Thereafter, 500 g of each category of pellets were placed in a tumbling box and tumbled at 50 ± 2 rpm for 10 min. After each tumbling process, the pellets were manually screened through 3,15-mm mesh sieve to separate the fines according to ISO 5370 (2023). The PDI was calculated as the percentage of pellets remaining on the sieve with the largest mesh size. The PDI was calculated as follows,

$$\text{PDI} = \frac{W_a}{W_i} \times 100 \tag{2}$$

where $W_{\mathrm{a}}$ is the weight of pellets retained on the sieve after tumbling (g), and $W_{\mathrm{i}}$ is the weight of pellets before tumbling (g). The percentage fines were calculated as Eq. 3,

$$\%\ \text{fines} = \frac{W_{pf} - W_p}{500} \times 100 \tag{3}$$

where $W_{\mathrm{pf}}$ is the weight (g) of pan and fines and $W_{\mathrm{p}}$ is the weight (g) of the pan.

### *Determination of proximate analysis and heating value*

The proximate analysis was evaluated by adopting, the British standard BS EN 15148:2009 method for determining the volatile matter. The ash content was determined in a muffle furnace at 580 °C in accordance with the method specified in ASTM D 1102-84. The fixed carbon content was calculated as the difference between the percentage total solid mass less sum of the percentage volatile matter and ash content.

The ISO standard ISO 18125 (2017) was adopted for determining the heating value of wood pellets. Samples of pulverized pellets were burnt in the ballistic bomb calorimeter, which automatically measured, the heat released by the combustion reaction to express the higher heating values.

Based on the mass yields and higher heating values (HHV), the energy density and energy yield for samples torrefied at different conditions were calculated as follows:

$$\text{Energy density}_{\text{(HHV)}} = \frac{HHV_{torrefied}}{HHV_{untreated}} \tag{4}$$

$$\text{Energy yield}_{\text{(HHV)}} = \text{mass yield} \times \frac{HHV_{torrefied}}{HHV_{untreated}} \times 100 \tag{5}$$

The lower heating values (LHV) were calculated based on (EPA 2007) (Eq. 6),

$$\text{LHV} = \text{HHV} - 10.55\ (W + 9H) \tag{6}$$

where $W$ is the weight percent of moisture in the fuel and $H$ is the weight percent of hydrogen in the fuel. For comparative purpose, the LHV were also used in calculating the energy density and energy yield for samples torrefied at different conditions as follows:

$$\text{Energy density}_{\text{(LHV)}} = \frac{LHV_{torrefied}}{LHV_{untreated}} \tag{7}$$

$$\text{Energy yield}_{\text{(LHV)}} = \text{mass yield} \times \frac{LHV_{torrefied}}{LHV_{untreated}} \times 100 \tag{8}$$

### *Method for determining NOX and $CO_2$ emission during combustion of pellets*

The emission of carbon monoxide (CO), carbon dioxide ($CO_2$), and nitrogen oxide (NOX) during the combustion of pellets was determined according to ISO 12039 (2001) and ISO 10849 (2022) specifications. The Thermo Scientific Nicolet iS50 FTIR Gas Analyzer was used to determine the CO, $CO_2$, and NOx of pellets. The analyzer used Fourier transform infrared (FTIR) spectroscopy to measure the absorbance of infrared light by different gases. The analyzer has a wide wavelength range (400 to 4,000 $cm^{-1}$) and a high signal-to-noise ratio, making it ideal for measuring the concentration of CO, $CO_2$, and NOx in pellets. The analyzer is equipped with features including; a heated sample chamber that allows for the analysis of hot gases, inlets that allow for the analysis of different types of gases, and a built-in data logging system that allows for the storage and retrieval of data.

The method involved measuring the concentration of the gases in the flue-gas produced during combustion. Combustion of dried samples was conducted in a chamber equipped to measure temperature, pressure, and other parameters during the combustion process. The concentrations of CO, $CO_2$, and NOX in the flue gas were also determined by the sensors at 10 min intervals for 120 min. These measurements were taken at different stages of the combustion process. The total particulate catch was calculated at the end of each combustion process.

## RESULTS AND DISCUSSION

The influence of torrefaction temperature on the weight loss of pellets is illustrated in Tables 1. The %weight loss of pellets and mass yield increased with increased torrefaction temperature. The result agrees with the findings of Park *et al.* (2020) that at 210 to 250 °C torrefaction temperatures and 50 min retention period, 7% to 55% mass reductions were observed. The weight loss between 225 and 300 ℃ torrefaction temperature was possibly due to the emission of volatile matter and thermal decomposition of hemicellulose, cellulose, and other wood cell wall polymers at a temperature above 228 ℃ (Mark *et al.* 2006; Gaitan-Alvarez *et al.* 2017). The heat treatment possibly eliminates less stable chemical components and preserves the higher molecular weight components, such as lignin, which is rich in carbon and inorganic constituents (Magalhaes *et al.* 2018; Wang *et al.* 2018). The finding agrees with previous studies that the mass yield of torrefied wood is related to thermal treatments, temperature, residence time, heating rate, and the nature of the feedstock. According to Yoshida *et al.* (2021), this observation implies that post-torrefied pellets have the disadvantage of a lower energy density compared with pre-torrefied pellets because of weight loss during torrefaction.

### *Water absorption*

The percentage of water absorption decreased with increasing torrefaction temperature (Table 2). Thus, the torrefied pellets were more hydrophobic because of their lower affinity for water absorption compared to their conventional raw pellets counterpart. Studies have shown that torrefied biomass has a lower water uptake than untreated pellets (Medic *et al.* 2012; Dyjakon *et al.* 2019; Lee *et al.* 2020; Yoshida *et al.* 2021). During torrefaction, the decomposition of hemicellulose components of wood destroys some of the hydroxyl (OH) group in the wood polymer, resulting in a change of structure and a reduction of hydrogen-bonding sites that can bond water (Lee *et al.* 2020) and reduces the capacity of torrefied material to adsorb water. Consequently, pellets torrefied at high temperatures have a low water uptake capacity, possibly due to the more intensive degradation of wood polymers and a reduction of hydrogen-bonding sites (Wang *et al.* 2020). Similar reports were made by Park *et al.* (2020), indicating that the torrefaction process increased the pellet hydrophobicity, possibly by destroying the H-O bonds, which hindered water absorption. In other words, torrefied pellets are less likely to degrade due to exposure to humid or moist environments, thus making them suitable for outdoor storage or other applications where water resistance is essential.

### *Percentage fine and pellets durability index*

The percentage of fines increased with torrefaction temperature, while the pellets durability index decreased with an increase in torrefaction temperature (Table 1). Pellets torrefied at 300 ℃ had the least PDI (82.7%) while pellets torrefied at 225 ℃ had high PDI value (98.0%). This trend conforms with the observation by Arouse *et al* (2021) that the durability of untreated pellets was 92%, while that of treated pellets at 300, 400, and 454 ℃ were 85%, 83%, and 84%, respectively. The mechanical strength of the pellets decreased with the increase in temperature, possibly due to the degradation of the hemicellulose and the removal of extractives and volatile compounds during the thermal treatment (Sarker *et al.* 2021). The loss of mechanical strength may also be attributed to the thermochemical degradation of lignin, a binding agent in the wood cell wall, which resulted in structurally unstable material (Gaitan-Alvarez *et al.* 2017; Adhikari *et al*. 2019).

These results agree with several other studies, which confirm that the increase in the torrefaction temperature considerably reduced the mechanical resistance of pellets, leading to high susceptibility to breakage and the generation of fines (Mustelier *et al.* 2012; Chen *et al.* 2015; Arous *et al*. 2021; Nunes *et al*. 2021).

### *Proximate analysis*

The proximate analysis results are indicated in Table 3. The percentage of volatile matter decreased with an increase in torrefaction temperature while there was an increase in the percentage of fixed carbon of torrefied pellets with temperature. The results are similar to the previous findings of Maxwell *et al.* (2020). The lower values of portion volatile matter at 250 and 300 °C were due to the thermal decomposition of hemicellulose, cellulose, and other wood cell wall polymers at a temperature above 228 °C (Mark *et al.* 2006; Gaitan-Alvarez *et al.* 2017). The removal of some of the volatile matter during torrefaction has been reported to increase the ignition temperature of pellets. This is expected to improve the storage of torrefied pellets since they are more difficult to ignite than raw pellets. The higher fixed carbon content of torrefied pellets also implies that torrefied pellets will burn more slowly and evenly than raw pellets, which can lead to a more efficient combustion process (Riaz et al 2023).

### *Higher heating value (HHV)*

The HHV of the pellets increased with the torrefaction temperature (Table 1). The lowest HHV of 18.9 MJ/kg was recorded for untorrefied pellets, while pellets torrefied at 300 °C had 29.9 MJ/kg. There was an increase in the energy density of the pellets with treatment temperature, while a slight reduction in energy yield was recorded (Table1).

**Table 1.** Physical and Heating Values of Pellets at Different Torrefaction Temperatures

| Properties | Control (Untorrefied) | 225 °C | 250 °C | 300 °C |
|---|---|---|---|---|
| Weight loss (%) | 0.00 | 7.96 ± 0.10$^{c}$ | 14.77 ± 0.81$^{b}$ | 26.35 ± 3.88$^{a}$ |
| Fine (%) | 0.16 ± 0.07$^{b}$ | 0.18 ± 0.12$^{b}$ | 0.29 ± 0.09$^{ab}$ | 0.39 ± 0.05$^{a}$ |
| PDI (Durability) | 98.82 ± 0.40$^{a}$ | 98.73 ± 0.53$^{a}$ | 95.73 ± 0.51$^{b}$ | 82.71 ± 0.30$^{c}$ |
| Higher Heating value (MJ/kg) | 18.93 ± 0.52$^{c}$ | 22.02 ± 0.08b$^{c}$ | 23.38 ± 3.65$^{b}$ | 29.86 ± 2.30$^{a}$ |
| Lower Heating value (MJ/kg) | 17.05± 0.47 $^{c}$ | 19.88±0.07 $^{b}$ | 21.06 ±3.29 $^{b}$ | 26.9 ± 2.07 $^{a}$ |
| Mass yield (%) | 100 | 92.04 | 85.23 | 73.65 |
| Energy density$_{(HHV)}$ | 1 | 1.16 | 1.23 | 1.39 |
| Energy yield$_{(HHV)}$ | 100 | 107.04 | 105.25 | 102.37 |
| Energy density$_{(LHV)}$ | 1 | 1.17 | 1.24 | 1.58 |
| Energy yield$_{(LHV)}$ | 100 | 107.69 | 105.68 | 116.2 |

Mean values with the same alphabet in each row are not significantly different (at p≤ 0.5) using the Ducan multiple range test.

The findings are similar to those of previous studies reporting that the heat treatment significantly improved the HHV of pellets (Yoshida *et al*. 2015; Park *et al*. 2020), while others confirmed that the higher calorific value increased from 18 to 19 MJ/kg (for untreated wood pellets) to 27 to 31 MJ/kg (for treated-wood pellets) (Saletnik *et al*. 2020; Arous *et al*. 2021). Torrefied pellets possibly had high HHV due to increased carbon content and decreased level of hydrogen and oxygen at high torrefaction temperatures (Wang *et al*. 2020).

Although the lower heating value (LHV) has less value than the higher heating value (HHV), the energy yield of the pellets calculated based on the LHV increased with increasing treatment temperature (as shown in Table 1). This is because the LHV deducts the heat of vaporization of moisture. The higher energy yield calculated based on the LHV for torrefied material is due to the reduction in moisture content and OH groups in the wood at high torrefaction temperatures. Similarly, previous reports in the literature indicated that torrefaction improved the heating value of pellets by increasing carbon content and reducing volatile matter content (Mustelier *et al.* 2012; Puig-Arnavat *et al.* 2012; Ghiasi *et al.* 2014).

The emission of large quantities of volatile matter in the temperature range of 120 to 150 ℃ might have resulted in an energy-densified product with a high heating value (Tumuluru *et al.* 2011; Nunes *et al.* 2021).

Studies have shown that biomass' carbon content increases at high torrefaction temperatures while hydrogen and oxygen are reduced (Wang *et al.* 2020; Alizadeh *et al.* 2022). Despite the slight reduction in the percentage of the hydrogen content of torrefied pellets compared with the untreated pellets, studies suggest that the proportion of hydrogen in the pellets contributes immensely to energy generation due to its high calorific value (Reis *et al.* 2012; Zhang *et al.* 2020). Thus, thermal treatment of pellets improved the energy density and combustion efficiency of torrefied pellets.

**Table 2.** Percentage Water Absorption of Pellets at Different Torrefaction Temperatures

| Immersion Time (h) | Torrefaction Temperature (°C ) | | | |
|---|---|---|---|---|
| | Control | 225 °C | 250°C | 300°C |
| 1 | 15.49 ± 2.05 | 13.16 ± 2.07 | 5.64 ± 0.75 | 5.34 ± 1.24 |
| 24 | 40.08 ± 0.94 | 39.52 ± 1.67 | 22.65 ± 4.48 | 15.90 ± 0.91 |

**Table 3.** Proximate Analysis of Pellets at Different Torrefaction Temperatures

| Properties | Torrefaction Temperature (°C ) | | | |
|---|---|---|---|---|
| | Control | 225 | 250 | 300 |
| Volatile matter (% db) | 77.1±0.1$^{a}$ | 74.9±0.8$^{a}$ | 70.1 ±0.2$^{b}$ | 64.1±0.5$^{c}$ |
| Fixed carbon (% db) | 21.7±0.2$^{b}$ | 23.5±0.5$^{b}$ | 27.8±0.51$^{a}$ | 32.8±0.2$^{a}$ |
| Ash (% db) | 1.2±0.1$^{b}$ | 1.6±0.1$^{b}$ | 2.1±0.1$^{b}$ | 3.1±0.2$^{a}$ |

Mean values with the same alphabet in each row are not significantly different (at p≤ 0.5) using the Ducan multiple range test.

## Emission during Combustion

The results of this study show that an increase in torrefaction temperature from 225 ℃ to 300 ℃ resulted in lower emissions of CO and $CO_2$ (Figs. 1a and 1c). The trend in the emission results agrees with previous research reports (Zhang *et al.* 2018; Nussbaumer *et al.* 2019; Li *et al.* 2020). Additionally, increased torrefaction temperature lowered the NOX emission, because the NOX emission was 13.33 ppm at 225 ℃ and 9.65 ppm at 300 ℃, respectively (Fig. 1b). The emission results of the current study conform with the findings by Li *et al.* (2020) that the NOX emissions were lower on a thermal and mass basis for the torrefied pellets compared to their non-torrefied counterparts.

There was, however, a slight decrease in total particulate matter (PM) in the combustion flue with an increase in torrefaction temperature (Fig. 1d). Thus, the content of PM emitted was reduced by torrefaction, possibly due to the degradation of polymers and low moisture in wood (Maxwell *et al.* 2020; Sarker *et al.* 2021). The results from PM quantification conform with previous studies on the pyrolysis fingerprints of torrefied biomass, which indicated that torrefaction reduced the concentration of sooting components, thus presenting a possible explanation for the reduction in fine particulate emissions during the combustion of torrefied pellets (Mitchell *et al.* 2016; Jia *et al.* 2020; Li *et al.* 2020; Yoshida *et al.* 2020).

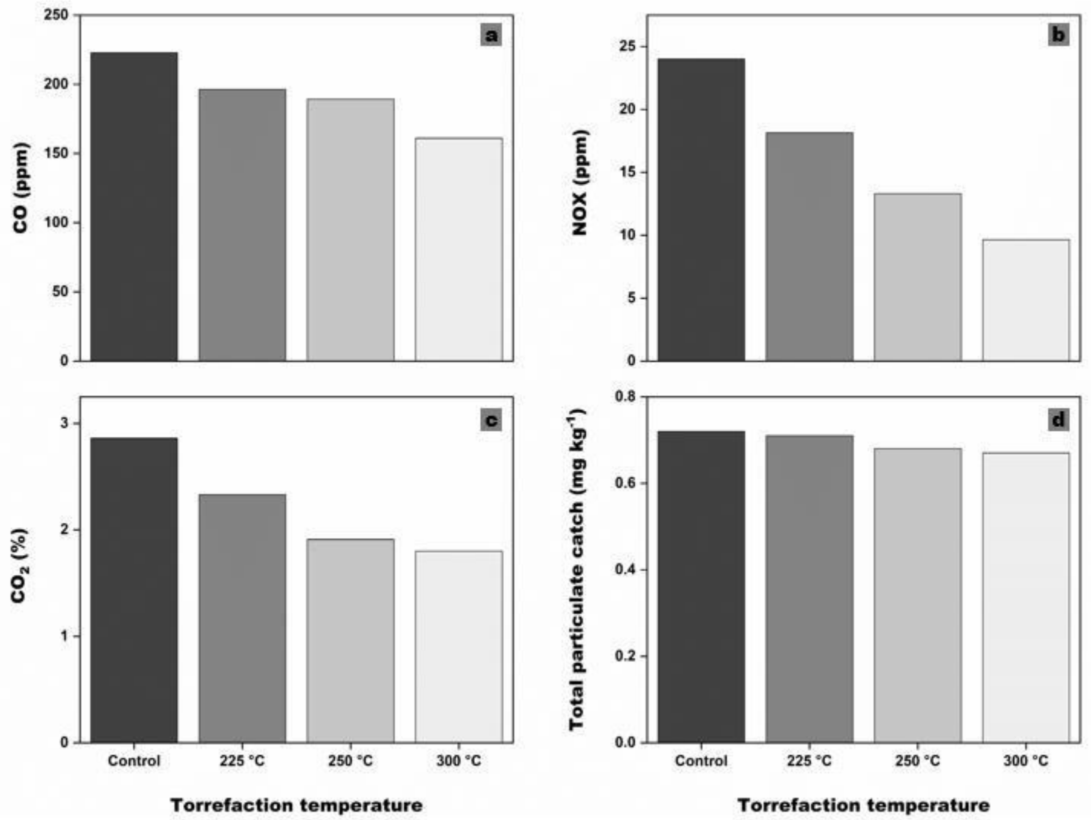

**Fig. 1.** The effect of torrefaction temperatures on emissions from pellets: **a**: Carbon monoxide, **b**: Nitrogen oxide, **c**: Carbon dioxide, **d**: Total particulate catch (Fig.1a Effect of torrefaction temperatures on CO emission; Fig.1b Effect of torrefaction temperatures on CO2 emission; Fig.1c Effect of torrefaction temperatures on NOx emission; Fig.1d Effect of torrefaction temperatures on Particulate Matter emission)

## CONCLUSIONS

1. The increase in torrefaction temperatures significantly affected the combustion properties and physical structure of torrefied wood pellets.
2. This study showed that torrefaction increased the heating value, energy density, and resistance to water uptake of torrefied pellets while there were reductions in CO, $CO_2$, NOX, and particulate matter emissions. The low percentage of $CO_2$ emission by the pellets corroborates that biomass is a carbon-neutral energy source because the carbon dioxide will subsequently be absorbed by trees during photosynthesis.
3. The increase in torrefaction temperature is a critical factor in improving the energy content of the pellets. Furthermore, the use of torrefied pellets as a low-carbon alternative to fossil fuels has the potential to reduce $CO_2$ emissions and promote sustainable energy production. With further research and development, torrefied biomass pellets can play a vital role in reducing the global carbon footprint and meeting the increasing energy demand in an environmentally friendly way.

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