



Research article

NO and SO₂ emissions from combustion of raw and torrefied biomasses and their blends with ligniteJale Yanik^{a,*}, Gozde Duman^a, Oskar Karlström^b, Anders Brink^b^a Faculty of Science, Department of Chemistry, Ege University, 35100, Bornova, Izmir, Turkey^b Åbo Akademi University, Faculty of Science and Engineering, Biskopsgatan 8, FI-20500, Åbo, Finland

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ABSTRACT

The impact of torrefaction on the NO and SO₂ emissions from combustion of biomass was investigated. Combustion experiments were carried out with two torrefied biomass fuels, i.e., poultry litter and olive tree pruning and their blends with lignite using a bench scale single particle reactor. For comparison, NO and SO₂ emissions from tests with untorrefied biomasses and their blends with lignite were also investigated. The total release of SO₂ and NO for each fuel was determined at three different temperatures: 900, 1000, and 1100 °C. The NO release from the untorrefied biomasses was found to be lower than those from torrefied biomasses, despite their higher fuel-N content. In case of co-combustion of both raw and torrefied biomass with lignite, the NO release was lower than the anticipated one. On the other hand, in the co-combustion experiments, blends with torrefied biomass showed a larger reduction in SO₂ release than the blends with raw biomass.

The study revealed that the SO₂ emissions from blends are not proportional to the mixing ratio of the fuels and to the emissions properties of the respective fuels. No clear correlation was detected between the NO_x emissions and fuel-N content. In addition to the NO and SO₂ emissions, the sintering propensity of the ash residue were investigated using scanning electron microscopy (SEM).

1. Introduction

Stringent environmental legislations for poultry litter have led to the need of alternative waste management options such as biochemical and thermal processes (Dalolioa F.S. et al., 2017). Combustion, as a thermal process, is the easiest way to convert the waste to a sterile material with a significant reduction in volume by 80–95% and to recover energy (Pandey et al., 2016). In combustion of poultry litter waste, the major environmental and operating problems are associated with its high moisture, nitrogen content and composition of its inorganic contents (Di Gregorio et al., 2014). Polesek-Karczewska et al. (2018) also remarked that the main issue regarding the efficiency of poultry litter combustion was closely connected to a low bulk density of the fuel bed.

One option in thermal conversion of poultry litter is co-combustion. Co-combustion of biomass or waste with coal is a simple and economically feasible way of utilizing biomass and waste and for replacement of fossil fuels. Co-combustion of biomass or waste with coal is a simple and economically feasible way of utilizing biomass and waste for replacement of fossil fuels. The co-combustion of lignocellulosic biomass is increasingly gaining importance as it represents

a low cost, sustainable, and renewable energy option that can provide reduction in net CO₂, SO₂ and often NO_x emissions (Sahu et al., 2014). Lower SO₂ emissions can be expected due to lower sulfur content of the biomass. In addition, the alkali in biomass should have the potential to retain sulfur in the ash as alkali sulfates. Zhang et al. (2013) observed significant reduction in SO₂ emission with an increased fraction of tobacco stem when blending with a high-sulfur bituminous coal. Similar results have been obtained for rice husk/coal blend (Huang et al., 2016), saw dust-coal blend (Kazagic and Smajevic, 2007) and agricultural wastes/coal blends (Narayanan and Natarajan, 2007). Despite its animalic origin, poultry litter waste is in many respects comparable with other biomass fuels. A number of co-combustion studies on poultry litter have been performed over the past decade. For instance, the influence of the combustion conditions on emission levels of pollutants such as SO₂ and NO_x during co-combustion of chicken litter and peat in fluidized bed combustion was investigated by Henihan et al. (2003) and Abelha et al. (2003). Abelha et al. (2003) found that the main problem associated with the combustion of poultry litter was the high moisture content which influenced its feeding to the combustor. Li et al. (2008) investigated the effect of co-combustion of poultry litter and coal on emissions in a fluidized bed combustor. They observed that addition of

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poultry litter into blend reduced the levels of SO₂. However, the level of NO either increased or decreased depending on the percentage of poultry litter in the blends. Junga et al. (2017) tested the technical and environmental performance of 10 kW understocker boiler during combustion of a blend of coal with laying hens mature. When 15% of the poultry litter was added to the coal, thermal output decreased (in about 20%) while CO and NO_x emission increased. The conversion of fuel blends of poultry litter and lignite has also been studied using thermogravimetric analysis (TGA). Yurdakul (2016) observed that with increasing coal content in the blend, the decomposition temperatures and burnout temperatures were shifted to higher temperatures, whereas combustion reactivity of the blends was decreased.

Although co-combustion is the least complicated and one of the most advantageous ways of utilizing biomass and waste in stationary energy conversion, there are technical challenges associated with co-combustion in existing coal power plants. The main challenges are poor grindability and low energy density of biomass. Torrefaction, i.e., mild heat treatment of biomass, is a promising way to improve fuel properties of biomass. Torrefaction of biomass can result in a less hydrophilic solid product with a higher heating value. In addition, the grindability may also be improved (Van der Stelt et al., 2011; Gil et al., 2015). Torrefaction has attracted significant interest in recent years. Most of the research has focused on the effect of process conditions and feedstock type on the product properties. A number of kinetic studies have also been undertaken in order to understand the combustion behavior of torrefied biomass. Despite the available knowledge on the combustion behavior of torrefied biomass, few studies have investigated poultry litter biochar behavior during combustion (Cimo et al., 2014; Novak et al., 2013). In addition, only few studies on the emissions from combustion of torrefied biomass have been reported in the literature (Li et al., 2012; Ndibe et al., 2015a,b). Moreover, one study has addressed the gas emissions from the combustion of poultry litter biochar (Mau and Gross, 2018). In that study, the gaseous emissions from biochar combustion were investigated with TGA–FTIR combustion experiments.

The European standard EN 14961-2 cannot fulfill the quality specifications for non-industrial pellets because of the specific characteristics of the raw material. It is clear that more research on residual biomass sources is needed to investigate their quality as fuels and the emissions generated during their combustion. In this study, differently from the studies in the literature, we investigated NO and SO₂ release from blends of lignite with four different biomasses: olive tree pruning and torrefied olive tree pruning, poultry litter and torrefied poultry litter. The study was performed using single particle reactor where single fuel pellets with different biomass to lignite ratio were combusted in a controlled gas atmosphere. In addition, the sintering propensity of the ash residues was analyzed using Scanning Electron Microscopy.

2. Materials and methods

2.1. Materials

The fuels used in this study included a Turkish lignite (from the Soma basin, Turkey), olive tree pruning (OP), torrefied olive tree pruning (OPB), poultry litter (PL) and torrefied poultry litter (PLB). The torrefied fuels were produced in a vertical furnace at 300 °C for a residence time of 30 min. Detailed information about the torrefaction process can be found in a previous work (Toptas et al., 2015). The properties of fuels are listed in Table 1.

Prior to combustion experiments, the fuels were dried in an oven and subsequently ground to a particle size less than 2 mm. Pellets were prepared from pure fuels and blends. The pellets were pressed using a manually operated hydraulic press. The diameter of the pellets was 8 mm. Instead of identical heights of the pellets, all pellets had a mass of 0.2 g. The blends of lignite and torrefied biomass and lignite and

Table 1
The properties of lignite, raw- and torrefied-biomass.

	Lignite	PL	OP	PLB	OPB
<i>Proximate analysis (wt.% dry basis)</i>					
Ash (at 550 °C)	11.5	8.2	3.3	12.8	4.1
Volatile matter	49.9	68.3	71.6	44.3	54.3
Fixed carbon	38.6	23.5	25.1	43.1	41.6
HHV, MJ kg ⁻¹	25.1	14.4	17.8	22.9	22.3
<i>Ultimate analysis (wt.% dry basis)</i>					
C	63.92	35.7	43.47	57.39	54.79
H	4.25	5.27	5.78	4.40	5.35
N	1.51	9.61	1.29	5.88	1.62
S	1.11	0.24	0.18	0.48	0.27
O	17.71	40.98	45.98	19.05	33.87
<i>Ash analysis (wt.% dry basis)</i>					
Na ₂ O	0.76	5.11	2.09	4.92	1.95
K ₂ O	1.41	26.53	22.48	25.82	21.56
CaO	2.48	39.52	59.78	41.21	61.28
MgO	1.73	6.22	6.94	7.05	7.35
SiO ₂	53.71	4.73	5.59	5.24	6.19
Al ₂ O ₃	24.08	1.09	0.86	1.55	1.05

untreated biomass were prepared by physical mixing. Four different blends of lignite and untreated biomass were prepared. The mass fraction of lignite in these samples were 25 wt%, 50 wt% and 75 wt%, referred to as 3:1, 1:1, 1:3 in figures. In the pellets containing lignite and torrefied biomass, the mass ratios were 50%.

2.2. Combustion experiments

The combustion behavior of the fuels and their mixtures were investigated using a single particle reactor, which consists of a quartz tube reactor in an electrically heated ceramic furnace. Before the tests started, the reactor was heated to the temperature at which the combustion experiments were to be conducted. The sample was inserted into the reactor using a movable probe. In this way, the sample could be shifted from room temperature into the hot reactor environment within a second. The main part of the gas enters through an inlet at the bottom of the reactor. A smaller portion of the inlet gas enters at the level where the fuel sample is inserted. This gas is needed to cool the sample before entering the reactor as well as to keep the viewing windows clean. A total flow rate of 220 l/h was used in all experiments. The gas flows were controlled using mass flow rate controllers. The composition of the exiting gas was analyzed with commercial analyzers: an AO2020 Continuous Emissions Analyzer (ABB, Germany) was used for CO, CO₂, and SO₂ analysis; O₂ was analyzed using a 4900 Continuous Emissions Analyzer (Servomex, England); and NO_x was analyzed using a Model 200EM chemiluminescence analyzer (Teledyne, United States). Based on the time resolved gas measurements and the known total flow, the total amount of NO and SO₂ were calculated integrating over the whole combustion time. A detailed description of the reactor setup and the experimental procedure can be found in Karlström et al. (2015).

The combustion experiments were conducted at three different temperatures: 900 °C, 1000 °C and 1100 °C. The highest temperature corresponds to the maximum achievable temperature of the electrically heated reactor. The two other temperatures were selected to be wide apart enough to obtain a trend without an excessive amount of experiment. The lowest temperature corresponds approximately to the bed temperature in a fluidized bed combustor, whereas the temperature 1100 °C is similar to that in the free board (Vainio et al., 2012).

A mixture of 3 vol % O₂ in N₂ was chosen to avoid very high particle temperatures in comparison to the reactor temperature because of exothermal oxidation reactions. Using an oxygen rich gas mixture, such as synthetic air, easily leads to particle temperatures several hundreds degrees higher than the reactor set point, and correlating the results to the reactor temperature becomes questionable. In addition, a gas with low oxygen content is representative for conditions inside a fluidizing

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