Gas emission study of a crop residue burning machine

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Abstract. Crop residue burning is a common agriculture practice to eliminate post-harvest vegetative material, which hinders the seedling of the next crop. A prototype of a crop residue burning machine was developed and equipped with six LPG burners. The burners were designed as a forced-draft burner where the air was supplied by a blower/pump. While open field burning is a practical and economical practice for controlling insects, diseases, and weeds, the environmental risks of this activity are an issue. Open biomass burning is a major source of global air pollutants and has a major impact on global climate change. This study aimed to estimate the concentration of CO and NOx emitted from the combustion using this prototype. CO and NOx are important indirect greenhouse gases that affect the formation of tropospheric ozone or change the lifetime of methane. The air pollutants were measured using ECOM-EN2. The gas velocity, static pressure, and gas concentration were sampled with 1 minute’s average sampling time. Gas emission study shows a high concentration of O2 in the flue gas. The recorded CO and NOx concentration exceeds the concentrations that regulated by EPA NAAQS. The average combustion efficiency of 98.0±0.3%, the highest emission factors for CO, NO, and NO2 are 57, 3.7, and 0.5 lb/acre, respectively.

1. Introduction

In Agriculture, fire is commonly used for removing crop residue when a large amount of residue is left by harvesting machines. This is necessary because a heavy amount of crop residues makes soil tillage for the next planting season difficult, especially when there has been insufficient time for the residue to decay [1]. Agricultural crop residues are produced during harvesting season in the form of stubbles, straws, and sugarcane leaves/tops. Since removing a large amount of crop residue is challenging, farmers prefer to burn the crop residue directly in the field. Burning crop residues is a fast and inexpensive practice to clear up and prepare the field for the next season [2][3].

Earlier studies have shown agriculture crop residue burning minimizes the incidence of rice stem rot in the rice paddy, control flag smut, twist disease, and wheat seed nematode [4]. Fire severity affects soil properties and vegetation. Light to moderate fire temperature is beneficial in increasing soil nutrients i.e. NO3-N, NH4-N, P, Ca, Mg, Na, and K, without significant difference in soil runoff and erosion [5]. Conversely, severe fire intensity can cause the removal of soil organic matter, loss of nutrients, leaching
and erosion, structure, and porosity degradation [6]. In a non-inversion tillage system, the large quantities of unweathered crop residues lead to residue toxicity. Field crop residue burning avoids the toxicity and maintains soil microclimate that is unfavorable to the development of soil disease. Besides, the presence of crop residue causes growth impairment, which is associated with emergence and growth rates [7].

Additionally, a frequent fire reintroduction has been used to control woody plants species that invade rangelands throughout the United States. This method is proven to be effective in maintaining livestock performance, carrying capacity, and stocking rate [8]. Fire-based wildland management is comparable to organic farming increasing total organism abundance and evenness [9].

While open field burning is practical and economical to control diseases weed and maintain soil health, the environmental and safety risks of the burning activity are still an issue. Agricultural crop residue burning emits a significant amount of greenhouse gases (CO₂, N₂O, CH₄), air pollutants (CO, NH₃, NOₓ, SO₂, NMHC, volatile organic compounds), particulates matter, and smoke [10]. Those pollutants have been considered to have a major impact on atmospheric chemistry and global climate change [3][11]. Furthermore, those pollutants cause health issues, especially respiratory problems, and PAH particles smaller than 2.5µm can pose a human health hazard by entering the pulmonary alveoli [2].

This study estimates the concentration of Carbon monoxide (CO) and Nitrogen Oxides (NOₓ) emitting by a crop residue burning machine. No publications were found regarding CO and NOₓ estimation from the combustion of crop residues using a burning machine. Those two pollutants do not directly influence climate change; however, those pollutants significantly impact atmospheric chemistry. CO alters the OH-CH₄-O₃ chemistry. A previous study indicated 100 Mt of CO would stimulate the emission of 5 Mt of Methane [12]. NOₓ has a crucial role in producing troposphere ozone and the formation of secondary inorganic aerosols [13]. Nitrous Oxide (N₂O) is one of the families of NO₃ compounds categorized as a “greenhouse gas”. This compound can absorb long wavelength radiation to hold radiating from earth, which contributes to global warming. Additionally, this substance reacts with both troposphere and stratosphere ozone leading to ozone depletion [14].

2. Methods

2.1. Experimental set-up

To estimate the concentration of CO and NOₓ, a prototype crop residue burning machine was used. The prototype was equipped with six air forced-draft burner in which air was supplied by an air compressor. Those LPG burners consist of two sets of three burners. The burners were placed in a pyramidal shaped hood. The dimension of the hood can be seen in Table 1.

All burners can be easily adjusted by varying the inclination with respect to the soil surface and angle difference. Furthermore, the difference angle between the three sets of burners on one side with the other three sets on the other side of the hood will allow staged combustion to occur, ensuring high combustion efficiency and low emission of unburnt pollutants. The LPG was supplied from a 250-gallon tank, and it was controlled and distributed by a supply network. The supply network consists of manual valves, solenoid valves, and pressure regulators. The operating pressure was set at 23 PSI, and the operating pressure for the pilot flame was 10 PSI. Propane-compatible hard piping and flexible hose rated for the required pressure supplied the propane from the tank to the burners. The amount of air supplied, and its static pressure was monitored using a flow meter and pressure gauge.

The combustion gases from the combustion chamber pass upward by a centrifugal blower with an adjustable speed drive through a-18 cm in diameter of the flue pipe. The air velocity, static pressure, and temperature in the stack were monitored using a digital thermo anemometer, a digital pressure transmitter, and a thermocouple, respectively.
Figure 1. The experimental set up of crop residue burning machine’s prototype. The arrow shows the operating direction.

Table 1. The dimension of the prototype crop residue burning machine.

| No | Part Description   | Dimension (cm) |
|----|--------------------|----------------|
| 1  | Square top base    | 64 x 64        |
| 2  | Bottom base        | 165 x 64       |
| 3  | Chamber height     | 51             |
| 4  | Stack diameter     | 18             |

2.5 ton/ha of switchgrass residues were placed on a rectangular tray, with eight 94 x 30 cm boxes filled with sand. The distance between the bottom edge of the hood and the tray was 7.6 cm, which resulted in the distance between the edge of the burner flares and crop residues was approximately 12.7”. The tray was driven by an adjustable speed motor in a trolley system. Additionally, the moisture content of the crop residues was determined according to the American Society of Agricultural and Biological Engineers (ASABE) standard ANSI/ASAE S358.3 [15].

The temperature inside the combustion chamber was measured using eight K-type thermocouples (Figure 2). This type of thermocouple has a limit of error of ±2.2°C. The temperature on hood’s surface was also recorded by measuring every vertex of the hood (A, B, C, D, E, F, G, H) using a digital infrared thermometer. The combustion temperature in the combustion chamber was then illustrated using MATLAB®.
Figure 2. Thermocouples arrangement for measuring combustion temperature in the combustion chamber. The red arrow shows the operating direction.

2.2. Determination of combustion condition
To evaluate the combustion conditions of the experimental system CO₂, O₂, CO, NO, and NO₂ concentrations were measured using gas analyzer ECOM-EN2. The analyzer was calibrated prior to use by the company operator. The accuracy for CO₂, NO, and NO₂ measurements was ±5% while the accuracy for O₂ and CO was ±0.2vol% and ±2%, respectively.

The gas velocity, static pressure, and gas concentration were sampled at 28” from the top of the hood. Gas velocity was measured using a digital manometer with its ±0.1% full-scale accuracy. The average sampling time for “MOVING” treatment was 0.55 minutes and for “STANDSTILL” treatment was 1.7 minutes. Combustion efficiency (CE) is determined using modified combustion efficiency (MCE), which assumes all the carbon is released as CO or CO₂.(1)

\[
MCE = \frac{\Delta[CO]_2}{\Delta[CO]_2 + \Delta[CO]}
\]

\(\Delta[CO]\) and \(\Delta[CO_2]\) are the mass concentrations of CO and CO₂ in excess of the background. Previous studies have demonstrated that over 95% of carbon is released as CO and CO₂. Therefore, it is accurate to estimate CE without considering hydrocarbons or PM.[16]

Emission Factor (EF) was calculated using equation (2)

\[
EF = \frac{\Delta C_x \times Q \times t}{A_{burned}}
\]

\(\Delta C_x\) is the measured pollutant concentration minus the ambient concentration. Q is the flow rate through the chamber, \(t\) is the sampling time and \(A_{burned}\) is the area of biomass burned. The velocity, static pressure, and temperature in the stack were also monitored.

2.3. Experimental design
The experimental design for gas emission measurement consisted of two levels of burner settings and two levels of travel speed with three replications. The first burner setting used only one set of burners that made up of three single burners, while the other set of burners remained off. The burner angle was at 67° with respect to the ground (1 SET). The second setting used two sets of burners consisting of six
single burners. One set of burners was at an angle of 67°, while the other burner set was parallel to the ground (2 SET). The amount of gas emission captured was also determined at 3 km/h (MOVING), and 0 km/h of travel speed (STANDSTILL).

3. Results and discussion

3.1. Combustion condition
The temperature of the combustion chamber for “1 SET” AND “2 SET” treatments was plotted and shown in Figure 3. The temperature of “1 SET” treatment was lower compared to the “2 SET” treatment. The highest temperature recorded by the thermocouple for “1 SET” and “2SET” was 457.29° and 638.84°.

![Figure 3. Combustion temperature recorded in the combustion chamber during the gas emission measurement experiment gas emission. (A) 1 SET (B) 2 SET.](image)

A high concentration of O₂ appeared in the flue indicates that more air was supplied than it was needed for complete combustion. For “MOVING” treatment, the concentrations were 15.82 (“1 SET”) and 14.86%-vol O₂ (“2 SET”) in dry flue gas, while “STANDSTILL” treatments were 11.10 and 12.7%-vol O₂ for “1 SET” and “2 SET”, respectively (Figure 4). The percentage of oxygen by volume in the flue of a combustion process is directly related to excess air. For biomass fuels combustion, the concentration 3 to 8%-vol O₂ in the flue suggests the excess air supplied for the combustion is 15 to 40% [17].

O₂ concentration is higher, the concentration of CO is decreasing. Even though the concentration of O₂ in the “STANDSTILL” treatment is lower, the concentration of CO is increasing rapidly. The high concentration of O₂ and CO in the flue indicates the air supply was not utilized by the crop residues (Figure 4).

Using a modified combustion efficiency equation, which assumes all the carbon is released as CO or CO₂, the combustion efficiency was 98.0±0.3%. The result agrees with the previous study on wheat stubble field burning that found the combustion efficiency for wheat stubble burning ranged from 92.2±0.5% to 97.7±0.3%. The lower combustion efficiency is partly due to higher stubble moisture content [18].

The flue gas temperatures were 285.7±38.9 °C for “MOVING” treatments and 480.7±21.4 °C for “STANDSTILL” treatments. Kruskal Wallis rank sum and Tukey HSD shows the flue gas temperature is not significantly different between “1SET” treatment and “2 SET” at α = 0.05. This excessive flue gas temperature is likely due to too much excess air was supplied for the combustion process. The excess air results in oxygen that are not consumed during combustion and this oxygen absorb otherwise usable
heat and carry it out of the flue. Furthermore, since the air was used as an oxidizer and most of the 79\% of air is N, it absorbs heat from the combustion of fuels.

![Image](image1.png)

**Figure 4.** The concentration of O\(_2\), CO\(_2\), and CO in the dry flue gas.

3.2. The concentration of CO and NO\(_x\)

CO emission factors (EF) for “MOVING” and “STANDSTILL” treatments are illustrated in Figure 5. The average EF for CO for “MOVING” treatments are 2.47±0.6 lb/acre and “STANDSTILL” treatments are 54.19±4.5 lb/acre. The more mass of crop residues was burned that resulted in the more flue gases were captured for “STANDSTILL” (S) treatments caused the EF was higher compared to “MOVING” (M) treatments. The statistical test (Table 2) shows that the EF for “1 SET” (1M and 1S) and “2 SET” (2M and 2S) are not significantly different (α =0.05).

EF results are difficult to compare against previous reports on biomass burning, due to the difficulties to quantify the weight of the burned fuel by the machine [19]. Additionally, when it is compared to EF for wildfires, the CO EF is extremely high, which the lowest EF for CO was 1258 lb/acre [20]. It is likely due to the difference in fuel type, activity rate, and fuel moisture content.

The recorded CO concentration exceeds the CO concentration that is regulated by EPA NAAQS. CO is one of EPA criteria air pollutants where its concentration in the ambient air should not exceed 35 ppm over a 1-hour period or 9 ppm over an 8-hour. During the study, all the gas measured over at least a 0.5-minute period [2]. The lowest CO concentration is 90.3 ppm and the highest is 1638.7 ppm (**Figure 6**).
Table 2. The results of the Kruskal-Wallis test and Tukey HSD for CO emission factors.

|                | Kruskal-Wallis Test | Tukey’s HSD |
|----------------|---------------------|--------------|
|                | X²                  | Df           | P-value | Interaction | P-value |
| Kruskal-Wallis | 8.46                | 3            | 0.04    | 1S-1M       | 0.02    |
| Wallis         |                      |              |         | 2M-1M       | 0.927   |
|                |                      |              |         | 2S-1M       | 0.015   |
|                |                      |              |         | 2M-1S       | 0.048   |
|                |                      |              |         | 2S-1S       | 0.99    |
|                |                      |              |         | 2S-2M       | 0.037   |

Oxides of nitrogen are the main pollutants produced by combustions, nitric oxide (NO), and nitrogen dioxide (NO₂). NO is the major NOₓ species that is emitted from a combustion process. Figure 7 depicts the NO emission factors for each of the four treatments. The average EF of NO for “MOVING” is 0.79±0.34 lb/acre and for “STANDSTILL” is 3.31±0.50 lb/acre. Similar to CO EF, the NO EF for “1 SET” and “2SET” treatments are not statistically different at α=0.05 (Nitrogen dioxide (NO₂) emission factor ranges from 0.24 to 0.54 lb/acre. Figure 9 illustrates the NO₂ emission factor for the combination of “MOVING” and “2SET” treatments is slightly higher than the other treatments. However, the EF values among the treatments are not significantly different from p-value =0.24 at α=0.05. NO₂ concentrations in the flue gas range from 5.7 to 16.2 ppm (Figure 10). The NO₂ concentrations are lower compared to the previous study that found the NO₂ concentration for conventional burner was 221 ppm at an air temperature of 500°C [21]. However, this concentration exceeds the primary and secondary standard of EPA NAAQS, which is 0.053 ppm annual arithmetic mean concentration [22].

The concentration of NO for “1 SET” treatments is higher compared to “2 SET” treatments (Figure 8). It is likely due to the higher concentrations of O₂ in the flue gas for “1 SET” treatments. At temperature above 1300 °C, NO is generated to the limit of available oxygen (approximately 200,000 ppm), however, at a temperature below 760° is generated in much lower concentrations. Emission regulations refer to NOₓ calculated as NO₂ because in the ambient atmosphere NO is oxidized within two hours [14].
Nitrogen dioxide (NO$_2$) emission factor ranges from 0.24 to 0.54 lb/acre. Figure 9 illustrates the NO$_2$ emission factor for the combination of “MOVING” and “2SET” treatments is slightly higher than the other treatments. However, the EF values among the treatments are not significantly different from p-value =0.24 at $\alpha=0.05$. NO$_2$ concentrations in the flue gas range from 5.7 to 16.2 ppm (Figure 10). The NO$_2$ concentrations are lower compared to the previous study that found the NO$_2$ concentration for conventional burner was 221 ppm at an air temperature of 500$^\circ$C [21]. However, this concentration exceeds the primary and secondary standard of EPA NAAQS, which is 0.053 ppm annual arithmetic mean concentration [22].

| Table 3. Kruskal-Wallis test and Tukey HSD for NO emission factor. |
|-------------------------|-------------------------|
| Kruskal-Wallis Test      |                        |
| $X^2$                   | 9.97                   |
| Df                      | 3                      |
| P-value                 | 0.019                  |
| Tukey’s HSD             |                        |
| Interaction             | P-value                |
| 1S-1M                   | 0.001                  |
| 2M-1M                   | 0.083                  |
| 2S-1M                   | 0                      |
| 2M-1S                   | 0.053                  |
| 2S-1S                   | 0.199                  |
| 2S-2M                   | 0                      |

![Figure 9. NO$_2$ emission factors (lb/acre).](image1)

![Figure 10. NO$_2$ concentrations in the flue gas (ppm).](image2)

4. Summary
This study focuses estimates concentration of Carbon monoxide (CO) and Nitrogen Oxides (NO$_x$). These pollutants do not directly influence climate change; however, those pollutants significantly impact on atmospheric chemistry. Gas emission study shows a high concentration of O$_2$ in the flue gas that suggests there was too much air supplied for the combustion resulting in heat loss through flue gas. With the average combustion efficiency of 98.0±0.3%, the highest emission factor for CO, NO, and NO$_2$ is 57, 3.7, and 0.5 lb/acre, respectively. The concentration of CO and NO$_2$ exceeds the amount regulated by EPA NAAQS. EF results are difficult to compare against previous reports on biomass burning due to the difficulties of quantifying the weight of the burned fuel by the machine.
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