Atmospheric Environment 98 (2014) 25–31

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Gaseous and particulate emission profiles during controlled rice straw burning

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HIGHLIGHTS

- We evaluated the effect of rice straw moisture on pollutant emissions during burning.
- Atmospheric emissions of CO_2, PM, dioxins, heavy metals, and PAHs were monitored.
- The main product obtained during the combustion process was CO_2, followed by PM.
- Emission factors of atmospheric pollutants were higher in 20% moisture treatment.

ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form
30 July 2014
Accepted 31 July 2014
Available online 1 August 2014

Keywords:
Biomass burning
Moisture content
Greenhouse gas
Particulate matter
Organic pollutants

ABSTRACT

Burning of rice straw can emit considerable amounts of atmospheric pollutants. We evaluated the effect of rice straw moisture content (5%, 10%, and 20%) on the emission of carbon dioxide (CO_2) and on the organic and inorganic constituents of released particulate matter (PM): dioxins, heavy metals, and polycyclic aromatic hydrocarbons (PAHs). Four burning tests were conducted per moisture treatment using the open chamber method. Additionally, combustion characteristics, including burning stages, durations, temperature, and relative humidity, were recorded. Burning tests showed flaming and smoldering stages were significantly longer in 20% moisture treatment ($P < 0.05$) compared with the rest. The amount of burned straw and ashes decreased with increasing straw moisture content ($P < 0.001$). Carbon dioxide was the main product obtained during combustion with emission values ranging from 692 g CO_2 kg dry straw^{-1} (10% moisture content) to 835 g CO_2 kg dry straw^{-1} (20% moisture content). Emission factors for PM were the highest in 20% moisture treatment ($P < 0.005$). Fine PM (PM2.5) accounted for more than 60% of total PM mass. Emission factors for dioxins increased with straw moisture content, being the highest in 20% moisture treatment, although showing a wide variability among burning tests ($P > 0.05$). Emissions factors for heavy metals were low and similar among moisture treatments ($P > 0.05$). Emission factors for individual PAHs were generally higher in 20% moisture treatment. Overall, emission factors of atmospheric pollutants measured in our study were higher in the 20% moisture content. This difference could be attributed to the incomplete combustion at higher levels of rice straw moisture content. According to our results, rice straw burning should be done after straw drying and under minimal moisture conditions to lower pollutant emission levels.

1. Introduction

Rice cultivation covers large areas of South-Eastern Asian countries (mainly China, India, Thailand, and Philippines) and localized regions of Spain, Italy, and North America. Post-harvesting field burning is still a common practice to remove straw cereals in many of these countries (Gadde et al., 2009). Burning rice straw poses benefits for the farmer since it controls weeds and reduces crop diseases, prepares the field for the next harvest, and releases nutrients for the following crop (Cheng et al., 2009; Gadde et al., 2009; Kadam et al., 2000; Lemieux et al., 2004). Rice straw burning, however, can contribute to impairing local air pollution, causing severe impacts on human health

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http://dx.doi.org/10.1016/j.atmosenv.2014.07.062
1352-2310/

(Gullett and Touati, 2003; Hays et al., 2005; Lin et al., 2007), particularly bronchial asthma (Arai et al., 1998; Torigoe et al., 2000).

Rice straw burning can emit considerable amounts of atmospheric pollutants, mainly carbon dioxide (CO_2) and particulate matter (PM). Other pollutants are also emitted during rice straw burning: carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), sulfur oxides (SO_x), non-methane hydrocarbons (NMHC), and some organic and inorganic compounds such as heavy metals, ions, volatile organic compounds (VOCs), dioxins (polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs)), and polycyclic aromatic hydrocarbons (PAHs), which are emitted in gas phase or as constituents of the PM (Andreae and Merlet, 2001; Cheng et al., 2009; Gadde et al., 2009; Hays et al., 2005; Lemieux et al., 2004; Zhang et al., 2008). Although some of these air pollutants such as PAHs or PCDD/Fs are released at low concentrations, they have harmful toxicological properties (Lemieux et al., 2004; Shih et al., 2008) and are potential carcinogens (Conde et al., 2005). Consequently, burning rice straw has been regulated and restricted in many regions worldwide despite its economic and practical benefits. For instance, in Spain, farmers continue to burn the straw and stubble that remains on the field after harvesting (Ortiz de Zárate et al., 2000).

Biomass burning includes two stages: flaming and smoldering; as well as a transitional state between them (Ogawa and Yoshida, 2005). During the flaming stage, the fuel mixture ignites, releasing mostly gases and soot particles (Andreae and Merlet, 2001). Once most volatiles have been released, the smoldering stage begins. The smoldering stage is a poor combustion phase, resulting from a low combustion temperature, insufficient mixing of fuel with combustion air, and a short residence time of the combustible gases in the combustion zone. Consequently, large amounts of incompletely oxidized pyrolysis products, such as CO, NMHC, ammonia, and the nitriles are released to the atmosphere (Andreae and Merlet, 2001; Khan et al., 2009). Khan et al. (2009) classified the pollutants emitted in a burning process into two classes: pollutants that are produced by combustion and unburned pollutants. Pollutants produced by combustion are emitted during the flaming stage, whereas unburned pollutants are usually produced in the smoldering stage.

Rice growers need economically viable and environmentally sustainable ways to manage large amounts of residual rice straw. Thus, there is a strong need for assessing environmental and health impacts of rice straw burning. In this framework, accurate and reliable emission data on rice straw properties and burning conditions affecting physicochemical profiles of gaseous and particulate emissions are required to reduce atmospheric pollution. Atmospheric emissions largely depend on the fuel and on the physical and chemical processes during combustion (Andreae and Merlet, 2001). Conde et al. (2005) found that when temperature and CO concentration drop during the combustion process (indicative of a reductive combustion with lack of oxygen) the quantity of PAHs decreased considerably independent from the device used for burning. Moreover, moisture content of rice straw can affect PAH emissions during rice straw burning (Korenaga et al., 2001; Lu et al., 2009). However, data on the effect of rice straw moisture content on other pollutants different from PAHs is still limited.

The objective of this study was to evaluate the effect of rice straw moisture content (5%, 10%, and 20%) during rice straw burning, on the emission of CO_2 and on the organic and inorganic constituents of released PM. A detailed quantification of dioxins, heavy metals, and PAHs in PM was performed. Combustion characteristics, including burning stages, durations, temperature, and relative humidity, were also characterized.

2. Material and methods

2.1. Experimental design: open chamber burn simulations

All tests were performed in an environmentally controlled chamber at the Institute of Animal Science and Technology of the Universitat Politècnica de València (Spain). The open chamber method was used (Miura and Kanno, 1997). Fig. 1 shows the distribution and dimensions of the environmentally controlled chamber.

The air inside the chamber was exhausted using a variable-speed wall fan (Exafan, Spain). The fan operated at a constant airflow rate of 2856 $m^3\ h^{-1}$, measured according to ASHRAE (2001) using a hot-wire anemometer (Model 425, Testo, Germany). Air was allowed to enter the chamber through 12 evenly distributed openings (0.6 m wide × 0.2 m high) located on the opposite sidewall. Air openings and airflow rate were established to simulate a wind speed over the straw surface ranging from 0.1 to 0.3 $m\ s^{-1}$, which was confirmed using a hot-wire anemometer (Model 425, Testo, Germany).

Three moisture contents of rice straw were evaluated: 5%, 10%, and 20% moisture. These moisture contents were selected to represent the most common straw moisture contents in field conditions (Gullett and Touati, 2003; Hays et al., 2005; Kadam et al., 2000; Korenaga et al., 2001). Moisture was achieved by sealing oven-dried straw (at 105 °C until constant weight) with different volumes of distilled water in plastic bags, until water was completely absorbed. Four burning tests (repetitions) were conducted per moisture treatment. Overall, a total of 12 burning tests were performed.

In each test, three kilograms of rice straw (wet basis) were weighed using a balance (KERN & Sohn GmbH, Germany). Two

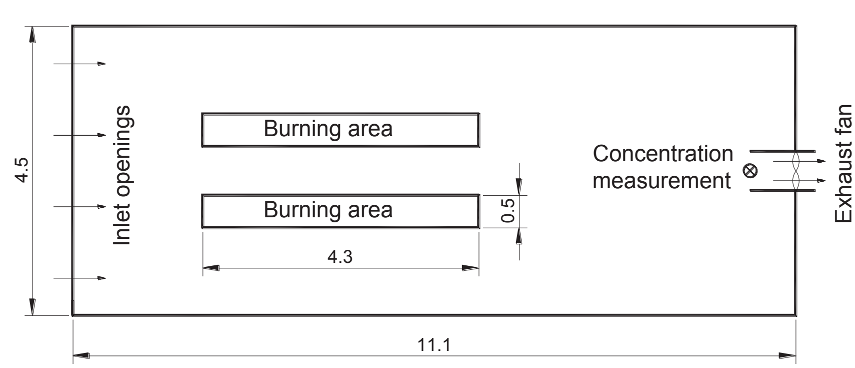

Fig. 1. Distribution of burning areas, air inlets and outlets, and concentration measurements in the environmentally controlled chamber. Dimensions in meters. Chamber height: 2.9 m.