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Particulate concentrations during on-farm combustion of energy crops of different shapes and harvest seasons

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HIGHLIGHTS

- Particulate matter (PM) concentrations ranged from 406 to 1417 mg Nm^{-3} (7 vol% O_2).
- PM levels failed Quebec's regulation and were high compared to literature data.
- Wood emitted 1.2 to 3.4 times less PM than four dedicated energy crops.
- Pelletized biomass generated less PM (22–52%) than uncompressed fuels.
- Spring-harvested crops reduced PM up to 48% compared to fall-harvested fuels.

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ABSTRACT

The increasing energy costs and environmental concerns of farms have motivated the growing interest of agricultural producers in using farm-grown biomass as a substitute to fossil fuels for heat production. However, the use of non-woody biomass is facing challenges due to variability regarding chemical composition and fuel properties that may induce problems during combustion such as particulate matter (PM). The aim of this work was to measure and compare total PM concentrations during on-farm combustion of wood and four agricultural crops: short-rotation willow, switchgrass, miscanthus and reed canary grass. In order to study the influence of physicochemical properties, different shapes (pellets, chips and chopped grasses) and harvest seasons (fall and spring) were also evaluated. In this context, a representative small-scale (29 kW), multi-fuel boiler for light commercial use was utilized. The boiler was also non-catalytic so that the burning took place in a single combustion chamber. Overall, twelve different biomass fuels were tested and each product was burned three times. Mean PM concentration of wood (416 mg Nm^{-3} at 7 vol% O_2) was lower than that of the four dedicated energy crops (505–1417 mg Nm^{-3} at 7 vol% O_2). However, because of the high variability between the experiments, no statistical significance was observed at $P > 0.1$ level except in one case. The PM amounts were high compared to literature data and Quebec's environmental regulation mainly because of the boiler system used. Except for willow, pelletized products decreased PM levels by 22–52% compared to chopped materials. Bulky biomass of low density was unable to reach steady-state conditions and produced compounds associated with incomplete combustion including PM. Spring-harvested biomass fuels showed a PM reduction up to 48% compared to fall-harvested crops. This was likely due to a 20–60% decrease of several chemical elements in the biomass, namely S, Cl, K and P which are the main constituents of fly ash.

1. Introduction

Worldwide, substituting fossil fuels by solar-based renewable resources has become a favorable option to face the increasing

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concentration of greenhouse gases (GHG) in the atmosphere and the rising cost of energy (Dhillon and von Wuehlisch, 2013). In this context, the agricultural sector in Canada, especially the province of Quebec, is currently looking at producing low-cost on-farm energy from crops grown on underutilized, surplus lands. The use of such biomass is particularly attractive for on-farm combustion systems since it represents a promising technique to provide heat for farm facilities where biomass boilers can replace oil- and gas-fired furnaces (Brodeur et al., 2008; Saidur et al., 2011).

Non-food crops for industrial purposes have been studied for more than twenty years in Europe and North America. As a result, short-rotation coppices (SRC), such as willow, and perennial rhizomatous grasses, such as switchgrass, miscanthus and reed canary grass, are now considered as the most promising dedicated energy crops (Lewandowski et al., 2003; Brodeur et al., 2008). These alternative biomass fuels, besides allowing the reduction of anthropogenic GHG emissions, show other ecological advantages. Their production involves limited soil management and minimal application of nutrient inputs. Purpose-grown energy crops can also serve for the restoration of marginal lands. In addition, the development of a biomass industry may create new employment opportunities in rural areas (McKendry, 2002). Nevertheless, the use of non-woody biomass is facing challenges due to variability regarding fuel properties that may induce combustion-related problems such as ash melting, deposit formation, corrosion and nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrogen chloride (HCl) and particulate matter (PM) emissions (van Loo and Koppejan, 2008). In Quebec's environmental regulation, the biggest concern is PM since the combustion of lignocellulosic biomass in small-scale units (<3 MW) is allowed but the concentration limit (70 mg Nm^{-3} at 7 vol% O_2) is more stringent than for wood combustion (150 mg Nm^{-3} at 7 vol% O_2). Therefore, there is a need for local scientific results to update the legislation (Villeneuve et al., 2012).

Particulate matter once released in ambient air affects air quality and climate. In fact, PM is consistently associated with adverse health effects since a chronic exposure to fine particles contributes to the risk of developing respiratory and cardiovascular diseases. Particulate emissions also influence the climate by absorbing and scattering sunlight and indirectly through their impact on cloud formation (Lamberg et al., 2011; Schmidl et al., 2011; Sippula, 2010). Total PM emissions are generally defined in two categories: PM_{10} and $PM_{2.5}$. The former represents coarse particles whose aerodynamic diameter is smaller than 10 μm. They are formed of non-volatilized ash and unburned fuel which are entrained into the flue gas. The latter is defined as fine particles whose aerodynamic diameter is smaller than 2.5 μm. Fine particles produced by small-scale combustion consist mainly of ash, elemental carbon and organic material. Fine ash particles, which are the dominant fraction under complete combustion, are formed after initial volatilization in the hot combustion chamber and subsequent condensation when temperature decreases. These flue ash particles are typically composed of alkali metals. Under incomplete combustion, particles can be found as soot and condensed heavy hydrocarbons (tar). Soot consists of elemental carbon entrained in the flue gas. When biomass is heated, soot decomposes into different organic compounds including tar which can remain in the flue gas due to low combustion temperatures, short residence time and lack of available oxygen. In some cases, tar is the main contributor to total PM emissions in small-scale solid fuel combustion applications (Kubica et al., 2007; Lamberg et al., 2011; Sippula, 2010; Tissari et al., 2008; van Loo and Koppejan, 2008).

The quantity and characteristics of PM produced are then strongly correlated to biomass physicochemical properties, combustion conditions and flue gas cleaning technology. The choice of biomass is crucial as chemical composition (ash, N, S, Cl, K, etc.) significantly differs between woody biomass (low), SRC (medium), herbaceous crops (high) and cereal straws (very high) (Obernberger et al., 2006; van Loo and Koppejan, 2008). Likewise, a delayed harvest until spring, i.e. when plants are chopped during fall, left on the ground all winter (where they undergo water leaching while snow melts) and harvested in May, can influence the crop composition by reducing the concentrations of most elements that lead to environmentally harmful emissions during combustion. In addition, physical properties mainly affect the efficiency of the combustion process. For instance, smaller particles increase the total surface area and the pore size of the material; they can also increase biomass consumption rate if a high density is maintained. For these reasons, compressing raw biomass into pellets is relevant. Besides increasing density, pellets improve physical homogeneity, contribute to a more uniform combustion and reduce pollutant emissions (Werther et al., 2000; Mani et al., 2004; Prochnow et al., 2009). Finally, small-scale biomass combustion is often an important source of fine particle emissions due to inexistent or inefficient flue gas cleaning system (Kubica et al., 2007; Schmidl et al., 2011; Sippula, 2010).

Several studies (AILE, 2012; Brassard et al., 2014; Carroll and Finnan, 2013; Carvalho et al., 2013; Chandrasekaran et al., 2013; Collura et al., 2006; Garcia-Maraver et al., 2014; Krugly et al., 2014; Schmidl et al., 2011; Sippula et al., 2007; Tissari et al., 2008; Verma et al., 2011) have recently investigated the influence of fuel physicochemical properties on PM amounts during small-scale combustion (7–60 kW) of different agricultural biomass materials. These works principally assessed the influence of biomass chemical composition through plant species, although other parameters like harvest period are of importance. Only Chandrasekaran et al. (2013) measured PM emissions from the combustion of three types of grass pellets from first or second cutting and leached in the field from October to December. Moreover, all aforementioned studies predominantly focused on pelletized fuels, even though densification requires expensive equipment and energy which thus raise the biomass cost (Werther et al., 2000). The effect of chopped products on PM emissions compared to pellets has merely been characterized by AILE (2012) and Collura et al. (2006) for miscanthus. Therefore, there is still a lack of knowledge regarding the environmental suitability of most promising energy crops harvested either in fall or in spring to be burned in different shapes in existing small-scale systems. The majority of the abovementioned studies were also carried out in Europe where biomass heating systems are generally more sophisticated than in North America. Fuel characterization with special attention to PM concentrations from a local, simple, cheap and multi-fuel boiler technology is actually needed before on-farm implementation. Such research can provide important information by showing the limitations of the current North American combustion technologies and by identifying key parameters and improvements required to adapt them for a broader spectrum of biomass fuels.

2. Materials and methods

2.1. Biomass fuels

Five different biomass fuels were used for this study: (1) a woody biomass (control) composed of black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*); (2) a SRC willow (*Salix* spp.); (3) switchgrass (*Panicum virgatum*); (4) miscanthus (*Miscanthus giganteus*); and (5) reed canary grass (*Phalaris arundinacea*). Wood was bought from a Canadian pellet mill (Granules LG, St-Félicien, QC, Canada), whereas willow was delivered by two Quebec's companies working in the bioenergy sector: Biopterre (La