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Influence of biomass properties on technical and environmental performance of a multi-fuel boiler during on-farm combustion of energy crops

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HIGHLIGHTS

- The efficiency (63–75%) varied depending on load, excess air and fuel ash content.
- Wood emitted less (0–94%) CO, NO_x, SO_2 and PM than agricultural crops.
- Pelletized biomass generated less (15–98%) CO, CH_4 and PM than chopped products.
- Spring harvest reduced (0–54%) NO_x, SO_2 and PM emissions.
- Fuel indexes allowed a rapid assessment of the suitability of biomass.

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ABSTRACT

More knowledge on combustion of agricultural crops is needed because of increased interest in using farm-grown biomass for energy production purposes. Presently, uncertainty regarding fuel quality and combustion-related emissions hinders the sustainable development of the agricultural biomass industry. The aim of this study was to evaluate the influence of physicochemical properties of biomass on gas, namely carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitrogen monoxide (NO), nitrogen dioxide (NO_2), ammonia (NH_3), sulfur dioxide (SO_2) and hydrogen chloride (HCl), and particulate emissions during on-farm combustion of wood and four dedicated energy crops: short-rotation willow, miscanthus, switchgrass and reed canary grass. Different shapes (pellets, chips and chopped grasses) and harvest seasons (fall and spring) were investigated. The thermal efficiency of the 29-kW boiler (63–75%) varied depending on energy load, excess air and fuel ash content. Wood emitted less CO (57–94%), NO_x (64–74%), SO_2 (0–93%) and PM (49–82%) during combustion than the four other solid biofuels. Higher emissions from the latter are due to their higher nutrient content. Pelletized products usually generated less CO (27–86%), CH_4 (15–98%) and PM (28–50%) than uncompressed materials. Reaching a constant combustion process with chopped biomass fuels turned out very difficult because of their heterogeneous particles and low density. The present work also revealed that delaying harvest from fall to spring reduced NO_x (0–11%), SO_2 (11–54%) and PM (0–37%) emissions. The 20–60% decrease of several chemical elements in the biomass due to leaching is likely responsible. Wood, willow, fall- and spring-harvested switchgrass and miscanthus pellets and willow chips seemed suitable to be burned in appropriate small-scale combustion units according to fuel indexes evaluation.

1. Introduction

The global increase in energy demand and cost has created a need for considerable research on renewable energy resources. In this context, biomass has gained rising interest since its use can decrease dependency on fossil fuels, as well as their associated environmental problems [1,2]. To intensify the presence of bio-

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mass in the energy sector, residues and wastes from agriculture and the food industry, short-rotation coppices and herbaceous crops can be used [3]. As a result, agricultural studies throughout Europe and North America have been focusing for the past two decades on introducing non-food crops for potential industrial applications. Fast-growing willow, switchgrass, miscanthus and reed canary grass have been considered as the most promising purpose-grown energy crops [4,5]. Besides contributing to the reduction of anthropogenic carbon dioxide (CO_2) emissions, these alternative biomass materials show other ecological benefits. They prevent soil erosion and require limited soil management and a low demand for nutrient inputs. Perennial energy crops also allow restoration of degraded, marginal or abandoned lands. In addition, the introduction of new biomass fuels may create job opportunities in rural areas [6]. Because of these potential advantages, the agricultural sector in the province of Quebec, Canada, is currently looking at producing low-cost on-farm energy from the conversion of dedicated crops grown on underutilized, surplus land. The use of raw biomass, with minimal processing, is particularly attractive for on-farm, small-scale combustion systems [5]. Direct combustion of biomass is a promising technique to provide heat for industries, homes and farm facilities where biomass boilers can replace oil- and gas-fired furnaces [1,7].

However, combustion of biomass causes emissions of gas and particulate matter (PM) which can seriously affect atmospheric processes and human health [8,9]. If pollutant emissions from wood combustion have been exhaustively investigated [10–16] and that small-scale wood combustion systems have been well developed to reach a high quality and performance level [17,18], burning non-woody biomass fuels in small-scale heating units is still a challenge in terms of ease of use, energy efficiency and air contaminants [18–20]. Compared to wood, agricultural materials usually contain less carbon (C) and hydrogen (H) and have higher contents in ash and inorganic elements such as nitrogen (N), sulfur (S), chlorine (Cl), potassium (K) and silicon (Si). Carbon and H impact the higher heating value (HHV). Hydrogen also has an effect on the lower heating value (LHV) due to the heat of vaporization of the water vapor (H_2O) [8,21–23]. High amounts of N, S and Cl in energy crops increase the emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2) and hydrogen chloride (HCl), respectively [8,22]. These gases can cause respiratory problems, acid rain, deposits and corrosion [8,9,22]. Ash contributes to dust emissions and operational problems such as fouling, slagging and corrosion. In small-scale appliances, they may disturb the combustion process, reduce efficiency and lead to unwanted shutdowns and higher levels of compounds from an incomplete combustion including carbon monoxide (CO) and PM [19,22–24]. Particles primarily consist of aerosol-forming elements like K and Cl, as well as S. Boiler corrosion and fouling are directly related to alkali and Cl contents. Chlorine acts as a catalyst, facilitating the movement of iron away from metal surfaces and the deposition or inorganic compounds. Sulfur and Si, in combination with alkali, lead to reactions associated with fouling and slagging in boilers. Silicon and K affect the ash melting behavior in dedicated energy crops [24–26]. Other ash-forming elements such as phosphorus (P), calcium (Ca), magnesium (Mg) and sodium (Na) have less impact on combustion, or have a relatively small range in concentration in biomass fuels [27].

The combustion of biomass is therefore strongly affected by the physicochemical properties. Numerous studies [18,19,24,28–44] have investigated their impact on emission levels and/or boiler performances during small-scale combustion (7–60 kW) of different agricultural residues and energy crops. In addition, most of these works [19,24,30–43] compared the combustion behavior of the selected agricultural fuels with commercially available wood pellets. These scientific articles primarily addressed the influence of chemical composition of biomass by assessing plant species, although other factors like stage of vegetation are very significant [21,45]. In fact, several studies [45–54] revealed that fuel quality is improved with delayed harvest because of a 20–80% reduction of the concentrations of most elements that lead to environmentally harmful emissions or ash-related problems during combustion (e.g. N, S, Cl, K and Si). The significant differences in chemical composition of different sorts of biomass harvested at different periods are often highlighted, but the corresponding impacts on emissions and ash-related problems stay relatively unknown. Only Chandrasekaran et al. [33] measured gas and 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. Besides chemical composition, fuel quality, emissions and ash-related problems can be influenced by the physical properties including particle size [11,45]. In fact, smaller particles increase the total surface area, the pore size of the material and the fuel consumption rate [55–59]. For these reasons, techniques to compress raw biomass into pellets are relevant [1,23]. Besides increasing density, pellets improve physical homogeneity, contribute to a more uniform combustion process and reduce pollutant emissions [23,24,40,55,58]. In this perspective, all aforementioned studies [18,19,24,28–44] predominantly focused on small-scale combustion of agro-pellets. Nevertheless, densification requires expensive equipment and energy which thus raise the fuel cost of agricultural residues and crops [23]. The effect of chopped products on emissions and ash-related problems compared to pellets has merely been characterized by AILE [40] and Collura et al. [42] for miscanthus.

Therefore, there is still a lack of knowledge regarding the combustion behavior of dedicated energy crops and their suitability to be burned in existing small-scale systems. The majority of recent studies [18,29,30,32,35,38,40,41] were carried out in Europe where biomass heating systems are generally more sophisticated than in North America. Fuel characterization with special attention to atmospheric emissions and ash-related problems from a local, simple and cheap 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. Since meeting high quality standards is problematic with agricultural biomass fuels in small-scale applications, the objectives of the present work are to evaluate: (1) the influence of physicochemical properties of biomass (species, composition, particle shape and harvest season) on gas and PM emissions and ash-related problems during on-farm combustion of different solid biofuels (wood, short-rotation willow, switchgrass, miscanthus and reed canary grass); (2) the technical performance of a 29-kW multi-fuel boiler when burning these biomass fuels; and (3) the suitability of energy crops to be burned in a technologically-simple boiler according to some fuel indexes developed.

2. Materials and methods

2.1. Biomass fuels

Five different biomass fuels were used for this study: (1) wood composed of black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*); (2) short-rotation 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 Pocatière, QC, Canada) and Agro Énergie (St-Roch-de-l'Achigan, QC, Canada). The three herbaceous