



# Ash behaviour and emission formation in a small-scale reciprocating-grate combustion reactor operated with wood chips, reed canary grass and barley straw



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## HIGHLIGHTS

- Two agricultural fuels were co-combusted with wood chips in a 40-kW boiler.
- Co-combustion of barley straw increased particulate emissions significantly.
- Co-combustion of reed canary grass caused only slight increase in emissions.
- Agricultural fuels did not increase the heavy metal contents in ashes.

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## ABSTRACT

The emissions and ash behaviour during combustion of wood chips, or co-combustion of two solid agricultural fuels (reed canary grass and barley straw) with wood chips, were studied. In addition, the sensitivity of the results towards different air-staging conditions was investigated using pure wood chips. The experiments were carried out in a 40-kW combustion reactor equipped with a reciprocating-grate burner. The addition of the reed canary grass to the wood chips increased only slightly the emission of fine particles (PM<sub>1</sub>), nitrogen oxides (NO<sub>x</sub>) and sulphur dioxide (SO<sub>2</sub>); while carbon monoxide (CO), hydrogen chloride (HCl), organic carbon (OC), elemental carbon (EC) and the geometric diameter (GMD) of the particles either decreased or remained unchanged. However, the number of particles emitted increased 2-fold in the reed canary grass combustion compared to the pure wood chips. In contrast, the addition of straw to wood chips substantially increased the emissions of PM<sub>1</sub>, CO, EC, SO<sub>2</sub> and HCl. The straw-originating particles were mostly crystalline KCl, and their number emission was clearly reduced, but their size was larger compared to the case with pure wood chips. The distribution of the combustion air had only a very minor influence on the release of the major ash species, whereas the effect was significant for the release of specific trace metals and the products of incomplete combustion. Finally, the partitioning of ash-forming elements with various fuels was evaluated based on chemical analyses of the fuel, bottom ash and fine fly ash fractions.

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## 1. Introduction

Attempts to reduce greenhouse gas emissions have increased the utilization of biomass in energy production. However, even though the amount of energy produced by renewables has increased, its overall share in total global energy production has decreased [1]. For example, the EU has set a target to increase the share of renewable energy in its total energy consumption to

27% by the year 2030 [2]. Achieving this goal will require increasing the production of biofuels, which creates a demand for alternative biomass sources and creates a greater need for fuel processing and emission control technologies. Utilizing agricultural fuels in small-scale heat production is a worthwhile option, considering local accessibility, financial benefits, and the reduction of CO<sub>2</sub> emissions. These agricultural fuels are typically available as either dedicated energy crops or as residues of feed crops.

The adoption of alternative biomass raw materials for energy production may lead to several disadvantages. First, small-scale biomass combustion units are known to generate high particulate

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matter (PM) emissions [3–5], especially through the use of alternative biomass raw materials, such as wood bark and straw [6–8]. It is generally agreed that particulate emissions have adverse effects on cardiopulmonary health [9–11] and influence the climate in several ways, including negative radiative forcing due to scattering and cloud formation [12] and the light absorbing effect of black carbon [13–16]. Second, the new biomass raw materials may substantially increase problems related to ash in solid fuel combustion systems, such as slagging in furnaces and the fouling of heat exchanger surfaces. While pure wood fuels are not considered to be particularly prone to slagging [17], many agricultural biomasses have a high tendency for slag formation due to high ash content and low ash melting temperatures [6,18]. Furthermore, agricultural biomasses often contain high amounts of alkali metals (K, Na), chlorine and sulphur which pose a risk for heat exchanger fouling and high- and low-temperature corrosion problems [19–22].

The behaviour of alkali metals, sulphur and chlorine in biomass combustion has been found to have large effects on the formation of PM emissions; in fact, the release of alkali metals is considered to be a major factor in PM formation in efficient biomass combustion systems (i.e., those systems without significant emissions of soot and organics) [7,21]. Furthermore, alkali release is of specific interest due to the fouling of superheaters in power-producing boilers [23]. The release of alkali metals is generally known to be affected by the inorganic composition of the fuel and the temperature conditions in the fuel bed, which is affected, e.g., by the air-staging settings [24]. Certain fuel properties, especially the ratios of Si/K, Cl/S, and Cl/K, have been highlighted as important in determining alkali metal release [25–28]. Generally, an increase in the Si content of the fuel tends to decrease the release of alkalis due to the formation of alkali silicates, but at the same time, it often decreases the ash-melting temperature and leads to slagging problems [17,29]. On the other hand, alkali release has been found to be significantly low in some phosphorus-rich fuels, most likely due to the formation of mixed phosphates in the bottom ash [30,31]. A high ratio of Cl/K favors the release of K into the gas phase as KCl, so the combination of K with silicates is decreased [26]. The behaviour of chlorine is also affected by the sulphur content of the fuel, and some studies have indicated that a sufficient S/Cl ratio may inhibit the effect of chlorine and decrease alkali metal release [25,27].

According to earlier studies [31,32], many trace metals (Zn, Pb, Cd, Cu, As, Tl, Ni and Cr) tend to be enriched in the fine particle fraction, while elements considered to be non-volatile (Fe, Ca, Mg, Al, Mn, Si, P) remain mainly in the bottom ash [33]. For some elements the volatility is highly dependent on the chemical composition of the fuel, for sulphur as an example [26]. It is important to understand the partitioning of metals between the bottom and fly ashes. First, trace metals in the fine particle fraction can significantly contribute to the toxic properties of particles [34–36]. Second, some trace metals (mainly Pb and Zn) are also known to promote the corrosion of heat exchangers [37]. Third, trace metal contents in collected ashes may limit their further utilization and disposal. In Finland, for example, regulations by the Ministry of Agriculture and Forestry define the maximum values for harmful substances (As, Hg, Cd, Cr, Cu, Pb, Ni, and Zn) and minimum values of nutrients (Ca, P+K) in forest fertilizers and field fertilizers [38,39] (SI Table 1). These limits are considered to be relatively strict, and often biomass ashes do not meet them [40].

Mixing the slagging or otherwise problematic fuels with pure and good quality fuels, such as wood chips, may improve combustion quality and reduce emissions. The positive effects may be based either on the diluting effect of the fuel with lower ash content [40] or more favorable ash composition [7,41]. The composition of the ash affects its melting temperature and the release of alkali metals. However, there is currently only a limited amount of

literature on the effects of biomass–biomass blending, and its potential for controlling emissions and solving ash-related problems has not been fully explored.

The objectives of this study were to compare emission levels and the properties of fine particles from wood chip combustion to emissions from the co-combustion of wood chips and two different agricultural fuels, reed canary grass (*Phalaris arundinacea*) (spring harvested) and barley straw (*Hordeum vulgare*) (autumn harvested), and to gain knowledge about the use of these types of fuel mixtures in small-scale boilers. Furthermore, the distribution of ash-forming elements between bottom ash and fly ash was studied to increase the understanding of the behaviour of the inorganic elements relevant to the formation of particle emissions. Because the behaviour of ash-forming elements and emission formation is influenced by air-staging settings, the sensitivity of the experimental results to combustion in various air distributions was also investigated.

## 2. Experimental section

### 2.1. Combustion appliance

The combustion experiments were carried out at the Fine Particle and Aerosol Technology Laboratory in the University of Eastern Finland using a novel modular combustion reactor for solid fuels (Fig. 1). The burner used for the measurements was a 40 kW multi-fuel stoker burner with a moving step grate (Ariterm Multi-jet). The grate had two rows of reciprocating blocks for improved fuel bed mixing and for preventing the molten ash from clogging the primary air feed holes, which allowed for the combustion of high ash content and melt-forming fuels. The combustion unit, including fuel feed and air supply, was logic-controlled. The fuel was fed from a storage silo to a drop hopper by screw conveyor, and from the drop hopper, it was dispensed to the grate by feed screw. The length of the grate was 300 mm, and the width was 165 mm. The dimensions of the combustion chamber were 395 mm × 285 mm × 845 mm (D × W × H). From the combustion chamber, flue gases were fed through a flue gas channel (150 mm × 150 mm) into the heat exchanger and then further into the stack where the particle and emission sampling points were located. The bottom ash samples were collected at the end of each experiment from under the burner at the bottom of the combustion chamber.

The combustion chamber and the flue gas channel leading to the heat exchanger were thermally insulated. The primary combustion air was supplied through the grate, which had air holes at the ends of the grate blocks. The secondary combustion air was supplied from the top of the side walls of the burner. The side walls were 150 mm high at the front of the grate and descended at a constant angle to 60 mm at the end of grate. Primary and secondary combustion air was fed into the combustion chamber by separate radial air blowers. The temperatures of the combustion chamber, flue gas channel and ambient laboratory air were measured continuously.

### 2.2. Combustion experiments

The first experiments were conducted with wood chips consisting of spruce (70%) and typical Finnish deciduous tree species (30%). The burner load in the air-staging experiments was held constant at 37 kW. The experiments were carried out with four different air-distribution settings (Table 1: wood 1–4) to reach the optimal settings for emission formation. The fractions of primary to total combustion air flows in the final experiments were 16%, 26%, 35% and 35% for the wood 1–4 settings, respectively.

In the co-combustion experiments, two agricultural fuels were mixed with wood chips similar to those used in the air-staging

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