

**Supporting Information for “A Biomass Combustion Chamber: Design,
Evaluation, and a Case Study of Wheat Straw Combustion Emission
Tests”**

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Table S-1. Summary of combustion chambers with their locations, specifications, basic parameters measured, and references to their use.

Location & Specifications	Fuel, Fire Ignition and Maintenance	Parameters Measured	Applications
<p>¹<i>Air Pollution Research Center of the University of California at Riverside, California, U.S.</i></p> <p>(Burning tower). A duct (made of tempered aluminum) in the form of an inverted funnel was placed over a burning platform (8 ft in diameter) positioned on a balance. An anemometer and a thermocouple was equipped in the exit stack to continuously measure air flow and temperature, respectively. Measurements were taken at ~ 731 cm from the burning source.</p>	<p>Range bursh (both dry and green), barley and rice stubble, and prunings from various fruit and nut trees in California. 25lb range bursh, 15lb barley, 15lb rice stubble, and 25lb prunings were burned for each individual burning test.</p> <p>A given weight of plant material was placed on the burning platform. One pound of barley straw was placed under woody and green plant material to assist in starting the fire. A small amount of alcohol was thrown on the edge of the pile of waste and ignited. Burning was usually conducted in the morning hours when winds were minimum.</p>	<p>Continuous records of CO₂, CO, and total hydrocarbon (HC) concentrations were made throughout the fire. Three grab samples for individual HC (ethene, alkene, and saturates plus acetylenes) analysis were made, one each being taken near to the time of the temperature peak, the HC peak, and at the end of the fire.</p>	<p>The burning tower was applied to study emission of CO₂, CO, gaseous HC, formaldehyde, organic acids, NO_x, particulate matter (PM), and polynuclear hydrocarbons from burning of municipal refuse, landscape refuse and automobile components (did not report where the fuel came) (Gerstle and Kemnitz, 1967), PM emissions, CO, CO₂, total HC, NO_x emission from grass stubble and straw collected from Oregon (Boubel et al., 1969), PM, CO and hydrocarbons emitted from burning of agricultural waste collected from California (Darley, 1977).</p>
<p>²<i>Department of Atmospheric Chemistry, Max Planck Institute for Chemistry in Mainz, Germany.</i></p> <p>A stainless steel hood in the form of an inverted funnel was placed over a 60 x 60 cm burning table on a high-resolution balance placed on a frame which stood on the ground outside to avoid vibrations. The platform could be tilted up to 45° from horizontal to simulate different wind directions. An electrical fan at the exit duct provided during low-temperature combustion to minimize the escape of non-ducted emissions. All the major part were made of stainless steel and mounted in a mobile trailer, which also contained most of the equipment required for carrying out the experiment. An anemometer was used to measure the flow rate of stack gases. Temperature sensors were equipped to determine both stack gas and fuel temperatures. Fresh exhaust for chemical analysis was sampled from the stack (approximately 2m above the burning platform).</p>	<p>Tropical grasses from savanna regions and also agricultural wastes (both were dry).</p>	<p>CO₂, CO, non-methane hydrocarbons (NMHC) and CH₄ as well as most important nitrogen-containing species: NO_x (NO and NO₂), NH₃, some cyanogen compounds such as hydrogen cyanide (HCN) and acetonitrile (CH₃CN), and nitrous oxide (N₂O).</p>	<p>The burn facility also characterized N₂O emission from burning savanna grass, straw, hay, oak, pine needles and litter of pine forest (Hao et al., 1991); nitrogen and carbon containing compounds from burning of savanna grass, wood, hay, straw, and forest fuels (Lobert et al., 1991); HO_x-producing gases (i.e., formaldehyde, acetaldehyde, methanol and acetone) from the burning of savanna grasses (Holzinger et al., 1999), major gaseous and particulate species (i.e., CO₂, CO, CH₃COOH, HCOOH, NO_x, NH₃, HONO, HNO₃, HCl, total volatile inorganic Cl and Br, SO₂ and particulate C, N, and major ions) emission from burns of southern African biomass (Keene et al., 2006).</p>

Table S-1, Continued

Location & Specifications	Fuel, Fire Ignition and Maintenance	Parameters Measured	Applications
<p>³<i>National Institute for Space Research, Brazil. São Paulo State University (Universidade Estadual Paulista, UNESP), Brazil</i></p> <p>Similar to the burning apparatus employed by Lobert et al. (1991, 1990), with the difference that the burning table of 1m ×1m in this study against 60 cm×60 cm in the previous studies.</p>	<p>Biomass samples representing Amazon forest native species (collected in the deforestation arc, near the town of Alta Floresta, state of Mato Grosso, Brazil) with moisture content ranging from 9%~11%, in terms of mass of moisture per total mass. Approximately 1.5kg of biomass was used for each experiment.</p> <p>A known amount of biomass loosely packed on the burning table was ignited by an LPG (liquefied petroleum gas) blowpipe. Biomass samples for each burning were composed of only one native species of the Amazonian forest. They were formed by 90% of twigs (mass percentage) with 2 cm² maximum cross-sectional area; the remaining were pieces of sticks and leaves of the same native species. Each experiment lasted 20-30min from ignition up to fuel bed cooling.</p>	<p>CO, CO₂, NO_x, and unburned hydrocarbons</p>	<p>/</p>
<p>⁴<i>National Risk Management Research Laboratory, United States Environmental Protection Agency, Research Triangle Park, North Carolina 27711</i></p> <p>(EPA's Open Burning Test Facility (OBTF))The facility was a ~20m³ (3.35m (L) × 2.72 m (W) × 2.21 m (H)) burn hut , with a 0.208 m³ steel burn barrel placed on a balance in the center. The barrel was sandblasted prior to use to remove any potential contaminants that would bias emission measurements. High-volume air handlers provided metered dilution air into the burn hut yielding approximately 2.46 air exchanges per minute. Additional fans were set up inside the burn hut to enhance mixing within the hut. There were thermocouples to measure temperature of sample duct, fuel, inlet air, flame, etc. Ambient air samplers were positioned inside the interior of the facility, and samples for the continuous emission monitors (CEMs) were collected from the sampling duct located on the wall with its inlet erected over the barrel.</p>	<p>Household waste (e.g., paper, plastic, food waste, textile/leather, wood, glass/ceramics, metal... etc.). The initial mass ranged from 6.4 kg to 13.6 kg per test, and the amount actually burned varied from 46.6% to 68.1%.</p> <p>Before each test, the material to be combusted was placed in the barrel; air flow through the facility was initiated; the material to be combusted was then ignited for a short period (< 3min) using a propane torch. Sampling was initiated at least 2min after removal of the propane flame, terminated when the burn mass did not change over an extended period. The sampling duration for each test ranged from 62min to 91min.</p>	<p>O₂, CO₂, CO and total hydrocarbons (THCs), HCl, PM_{2.5}, polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDDs/PCDFs)</p>	<p>The U.S. EPA's Open Burning Test Facility (OBTF) yielded emissions from burning of U.S. household waste (Gullett et al., 2001; Lemieux, 1997), forest fuels (Gullett and Touati, 2003; Hays et al., 2002) and crop residues (Dhammapala et al., 2006; Dhammapala et al., 2007; Gullett et al., 2006; Hays et al., 2005; Kleeman et al., 2008).</p>

Table S-1, Continued

Location & Specifications	Fuel, Fire Ignition and Maintenance	Parameters Measured	Applications
<p>⁵(Simulation Fire Test (SIFT) chamber). The chamber had a dimension of 4×3×2m³ sizes and having 0.2 μm high-efficiency particulate arrester (HEPA) filter bank at the inlet side. At the other end, induced draft (ID, 1m³ s⁻¹) had been provided to evacuate the chamber before the start of each experiment. Before the ID, a pack of pre-filter had been provided. In the centre of the chamber was a pan of an electronic balance, where the biomass burned. Particulate and gaseous samples were collected from the roof of the chamber, 2m from the burning source.</p>	<p>Garden biomasses collected from Delhi, India, namely grass, leaves, twigs and mixtures of these three. The biomasses were air-dried. 15~100g biomass was burned per test.</p> <p>The chamber was completely evacuated before the start-up of the experiment to remove residual aerosol and gases of the previous experiment. Initially 2ml of methylated spirit was burnt, which was used to initiate fire of biomasses during various experiments. The combustion was generally completed in 6-10min. After homogenisation, air samples were collected or monitored. The duration of sampling is 5min.</p>	<p>Gaseous products such as NO_x, CO, HC and CO₂; particulate emission and particle size distribution</p>	<p>/</p>
<p>⁶Max Planck Institute for Chemistry in Mainz, Germany.</p> <p>A 60cm×60cm tiltable metal plate attached to a balance was placed under a static ventilation inverted funnel, which was connected to a chimney leading to a 32.6 m³ container. Two fans located at the side of the container led the emission continuously to the container during the experiment, where the smoke was diluted with the ambient air with an average flow rate of 3.8 m³/min. Online gaseous (e.g., CO, CO₂, NO) measurements were taken from a chimney above the funnel. The aerosol samples were drawn to a dilution tunnel (which was connected to particle sampling devices) with a flow rate of 11.5 L/min using a stainless steel tube (~1.5m length and 25 mm internal diameter). The residence time of the gas and particle mixture in the sampling system was kept to a maximum of 9 min to minimize particle modification in the sampling system.</p>	<p>Dried European conifer species, savanna grass, African hardwood, and German and Indonesian peat.</p> <p>All biomass fuels were weighed prior to and during the experiment. The biomass fuels were ignited using a butane burner. The biomass fuel was combusted continuously for approximately one hour to maintain fresh smoke in the container. The smoke was sampled continuously for approximately 50 to 60 min during the course of stable combustion. Then the chimney connecting the fireplace to the dilution container was switched from a bypass position to the sampling position to fill the container volume with emissions from combustion. A small piece of biomass fuel of known mass was added to the fireplace regularly in order to keep the fire from extinguishing.</p>	<p>water-soluble organic carbon (WSOC), water-insoluble organic carbon (WISOC), OC, EC, inorganic ions, n-alkanes, n-alkenes, PAHs, oxy-PAHs, lignin decomposition products, nitrophenols, resin acids, and cellulose and hemicellulose decomposition products. CO, CO₂, NO</p>	<p>/</p>

Table S-1, Continued

Location & Specifications	Fuel, Fire Ignition and Maintenance	Parameters Measured	Applications
<p>⁷<i>The Fire Sciences Laboratory (FSL) of the US Forest Service in Missoula, Montana</i></p> <p>The main combustion chamber was a square room with internal dimensions 12.4 m (L) × 12.4 m (W) × 19.6 m (H) and a total volume of ~3000 m³. An exhaust stack, with an inverted funnel at the bottom narrowed from a 3.6 m diameter opening to the 1.6 m stack diameter, located at the center of the room began 2.1 m above the floor and extended through the chamber ceiling. A 46cm×61cm horizontal metal tray, namely fuel bed, positioned on a balance and located directly beneath the inverted funnel. Sampling ports that originated near the center of the stack flow and passed through the walls of the exhaust stack were located ~16.5 m above the floor, and were accessed from a measurement platform (where temperature, pressure, trace gases, particulate measurements were deployed) near the ceiling.</p>	<p>33 different plant species, included the chaparral species chamise, manzanita, and ceanothus, and species common to the southeastern United States (common reed, hickory, kudzu, needlegrass rush, rhododendron, cord grass, sawgrass, titi, and wax myrtle). Fuel that were too moist to burn were dried at 35~40 °C for 48-72h. Initial fuel masses ranged from 25 g to 2500 g depending on the objective of the experiment and desired emission concentrations; most were between 100 g and 250 g.</p> <p>Fuels were stacked horizontally on the fuel bed to facilitate ignition, except for two large fuel mass burns (2500 g) when fuels were stacked in a cylindrical wire cage. Several methods were used to ignite the fuel. Dry fuels were ignited using a butane pilot lighter applied briefly to the edge of the fuel bed. Fuels with high fuel moistures required the application of a propane torch or heated metal coils for a significant period of time, in some cases continuously, to maintain the fire. Both ignition methods often resulted in a propagating flame front that moved through the fuel bed and simultaneous flaming and smoldering combustion in different parts of the fuel bed. There were also fuels placed on a lattice of heating tape that was soaked with 15g of ethanol, which was vaporized and ignited on heating, uniformly igniting the fuel bed.</p>	<p>gas-phase CO₂, CO, CH₄, C2-4 hydrocarbons, NH₃, SO₂, NO, NO₂, HNO₃, and particle-phase organic carbon (OC), elemental carbon (EC), SO₄²⁻, NO₃⁻, Cl⁻, Na⁺, K⁺, and NH₄⁺</p>	<p>The Forest Service Fire Science Laboratory (FSL) used a large combustion chamber (a total volume of ~3000 m³) with wildland fuels to study emission factors/ratios, source profiles and organic markers (Bertschi et al., 2003; Burling et al., 2010; Chen et al., 2007; Chen et al., 2006; Christian et al., 2003; Freeborn et al., 2008; Friedli et al., 2003; Goode et al., 1999; Griffith et al., 1991; Lee et al., 2010; Levin et al., 2010; Mazzoleni et al., 2007; McMeeking et al., 2009; Obrist et al., 2007; Sullivan et al., 2008; Warneke et al., 2011; Yokelson et al., 2011; Yokelson et al., 2008; Yokelson et al., 1996); different emission characteristics during the flaming and smoldering phases (Lee et al., 2010; McMeeking et al., 2009; Yokelson et al., 1997); the size, morphology and microstructure of particles (Chakrabarty et al., 2006); aerosol hygroscopicity, cloud condensation nuclei (CCN) and ice nuclei (IN) activity (Carrico et al., 2010; DeMott et al., 2009; Petters et al., 2009a; Petters et al., 2009b); and optical properties of smoke particles (Lewis et al., 2009; Lewis et al., 2008; Mack et al., 2010). Recently, Stockwell et al. (2014) used open-path Fourier transform infrared (OP-FTIR) spectroscopy system and other instruments to measure trace gases, including CO₂, CO, CH₄, ethyne (C₂H₂), propylene (C₃H₆), formaldehyde (HCHO), formic acid (HCOOH), methanol (CH₃OH), acetic acid (CH₃COOH), glycolaldehyde (C₂H₄O₂), furan (C₄H₄O), water (H₂O), nitric oxide (NO), nitrogen dioxide (NO₂), nitrous acid (HONO), NH₃, hydrogen cyanide (HCN), hydrogen chloride (HCl), and SO₂ (Stockwell et al., 2014).</p>

Table S-1, Continued

Location & Specifications	Fuel, Fire Ignition and Maintenance	Parameters Measured	Applications
<p>⁸<i>Desert Research Institute Division of Atmospheric Sciences, USA</i></p> <p>The flow dilution is controlled through an adjustable speed exhaust fan. By changing the speed of the fan, the amount of room air sucked into the chamber is controlled, thus the dilution rate. At maximum flow rate, 1 m³ per min air is pulled into the chamber that is 8 m³ in volume. At this flow rate, the smoke temperature is immediately cooled to room temperature.</p>	<p>The fire is either ignited with a propane torch or using a heated coil. Once the fuel is lit, it is allowed to burn until the fire stops. Ponderosa pine needles – 50 grams – dry (8.2% moisture content), Cheat grass – 40 grams – dry (6.7% moisture content), Alaskan peat– 22 grams at 25% and 20 grams 50% moisture content), Siberian peat – 23 grams (25% and 50% moisture content), and Florida swamp peat– 25 grams (25% moisture content) were burned.</p>	<p>CO, CO₂, H₂O, aerosol particle number and size distributions, NO, NO₂, NO_x, aerosol light absorption, and black carbon concentrations are measured continuously.</p>	<p>/</p>
<p>⁹<i>Fudan University, China</i></p> <p>The experimental system consisted of a custom-made combustion stove (60 cm in diameter 80cm in height) and a stainless-steel environmental aerosol chamber of 4.5m³, equipped with a set of analytical instruments. The top of the stove was connected to the aerosol chamber through a stainless steel tube (diameter16mm). Air was introduced into the combustion stove through a port on the bottom. A hygroclip monitor was used to measure the temperature and relative humidity (RH) inside the chamber. A mixing fan was installed at the bottom of the chamber to give the air in the chamber full mixture. This system was able to control temperature from 203K to 373K and pressure from 14Pa to 0.22MPa.</p>	<p>Three major agricultural crop residues in China: rice, wheat, and corn straws. The rice straw was collected from a rural field in the suburbs of Shanghai, and the wheat and corn straw were from a rural region in Hebei province, China. About 20g of straw was burned for each experiment.</p> <p>Agricultural crop straw was weighed before and after each burning, and the unburned fraction and ash were collected for weighing. Before each burning, the chamber was purged by scrubbing and blowing air and then vacuumed to below 100 Pa. The agricultural crop straw was ignited with a propane torch in the stove. Then, the smoke produced was introduced into the chamber immediately by turning on the controlling valve until the pressure between the inside and the outside was equal. In the experimental processes, ambient air was introduced into the chamber through an activated charcoal filter and a filter, to maintain the pressure equilibrium in the chamber.</p>	<p>NO_x (NO and NO₂), CO, CO₂, particulate number concentrations</p>	<p>This burning facility was used to determine particle size distribution and polycyclic aromatic hydrocarbons (PAHs) emissions from the burning of rice, wheat, and corn straws, three major agricultural crop residues in China (Zhang et al., 2011).</p>

Table S-1, Continued

Location & Specifications	Fuel, Fire Ignition and Maintenance	Parameters Measured	Applications
<p>¹⁰<u>Chiang Mai University, Chiang Mai 50200, Thailand</u></p> <p>A stainless steel burning facility consists of a burning chamber (0.50m in diameter, 1.20m in height) equipped with a burning basket and a temperature sensor, and a storage chamber (0.85m in diameter, 2.0m in height) equipped with a Minivol Portable Air Sampler (Airmetrics, USA), gas analyzer (350-XL, Testo, Germany) and vacuum pump (FY-1.5B, Mizu, Thailand).</p>	<p>Rice straw, maize residue and forest leaf litter (average moisture content was 9.32%, 6.51% and 12.20%, respectively) were collected from Chiang Mai Province, Thailand. 10g sample was used in the burning of maize residue and leaf litter, 20g was used in rice straw burning.</p> <p>Before the burning, air inside the storage chamber was pumped out to reach a near vacuum condition. A biomass sample was put into a basket inside the burning chamber. Liquefied petroleum gas was used for ignition. The burning of each fuel type took about 1 min and the temperature of the burning was between 500 and 800°C. After the fuel was burned out, a valve set up between the burning chamber and the storage chamber was opened. The pollutants emitted from the burning were drawn into the storage chamber. Concentrations of gases including CO, NO, NO₂ and SO₂ were continuously measured for approximately 5 min using a gas analyzer. After that, the air inside the storage chamber was drawn out using an air sampler at a flow rate of 5 L min⁻¹ and the PM₁₀ were collected on a pure quartz fiber filter (47 mm, Whatman, UK) for 5 h.</p>	<p>CO, NO, NO₂, SO₂, PM₁₀, and ions in PM₁₀ (HCOO⁻, Cl⁻, NO₃⁻, PO₄³⁻, SO₄²⁻, Na⁺, NH₄⁺, K⁺, Ca²⁺, Mg²⁺)</p>	<p>/</p>
<p>¹¹<u>Peking University, China</u></p> <p>A stainless steel hood with skirt was erected over a combustion pan (dimensions 1.5×1.5m²) which was placed on an electronic balance. Smoke emitted was collected by the hood before going through a custom-made dilution tunnel and residence chamber. A S-type pitot tube and a temperature sensor was equipped in the dilution tunnel. The residence chamber had a volume of 50L, which needed about 30s for air flow to pass prior to particle sampling. Temperature in the residence chamber was not higher than 40°C.</p>	<p>Air-dried rice straw and sugarcane leaves collected from cultivated land in Pearl River Delta (PRD) region, China. 300~994g biomass were burned for each test.</p> <p>The biomass was stacked horizontally on a burning pan.</p>	<p>CO₂, CO, non-methane hydrocarbons (NMHCs), oxygenated volatile organic compounds (OVOCs), PM₁₀, PM_{2.5}, OC and EC in PM_{2.5}</p>	<p>/</p>

Location & Specifications	Fuel, Fire Ignition and Maintenance	Parameters Measured	Applications
<p>¹²<u>Institute of Agro-Environmental & Forest Biology (IBAF), National Research Council (CNR), Italy</u></p> <p>The stainless steel chamber had a size of 106cm (L) × 80cm (W) × 50cm (H) with an exhaust chimney in 10 cm diameter. A 16cm×16cm stainless steel burning basket covered by a grid placed on a high resolution balance was equipped with to burn biomass. An adjustable electrical fan was placed at the bottom of the chamber to deliver air to the chamber. The chamber was also equipped with a data logger to store the air flow rate measured by an anemometer, a thermocouple to record temperature of the fuel bed and exit stack gas during the combustion, an epiradiometer placed just over fuel bed and two different sampling lines.</p>	<p>Dried leaf litter of <i>Quercus robur</i> collected from Mediterranean forest areas (~50g for each test).</p> <p>The biomass was placed on the burning basket, and the epiradiometer was placed just above the fuel at a distance of 1cm for ignition. The fan speed was regulated to maintain a constant air flow of 0.7 m/s inside the chimney to provide a good circulation of air within the chamber ensuring a good supply of oxygen.</p>	<p>CO, CO₂, VOCs, PM.</p>	<p>/</p>

Detailed description please refer to: 1. (Darley et al., 1966); 2. (Lobert et al., 1990); 3. (Soares Neto et al., 2011); 4. (Lemieux et al., 2000); 5. (Kamalakkannan et al., 2004); 6. (Inuma et al., 2007); 7. (McMeeking et al., 2009); 8. Personal communication; 9. (Zhang et al., 2008); 10. (Sillapapiromsuk et al., 2013); 11. (Zhang et al., 2013); 12. (Lusini et al., 2014).

Table S-2. Parameters used to estimate EFs taking one wheat straw combustion test as an example.

	CO ₂ ^b	CO ^b	PM _{2.5} ^c	OC ^c	EC ^c
t _{sample} (s)	450	450	450	450	450
∑ C _{Dil,i} ^a (mg m ⁻³)	357713	13969	/	/	/
m _{filter} (mg)	/	/	0.124	0.031	0.010
Q _{filter} (m ³)	/	/	0.0375	0.0375	0.0375
DR	5	5	5	5	5
V _{Stk} (m s ⁻¹)	3.86	3.86	3.86	3.86	3.86
D (m ²)	0.0177	0.0177	0.0177	0.0177	0.0177
m _{fuel} (g)	85.37	85.37	85.37	85.37	85.37
EF(g/kg)	1431	55.90	5.95	1.49	0.48

- a. ∑ C_{Dil,i} is an integral value during the whole sampling from t=1 to t=t_{sample};
- b. EF was calculated by Equation (1) in the text;
- c. EF was calculated by Equation (2) in the text.

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