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Chemical composition and emissions factors for cookstove startup (ignition) materials

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Abstract

Air pollution from cookstoves creates a substantial human and environmental health burden. A disproportionate fraction of emissions can occur during stove ignition (startup) compared to main cooking, yet startup material emissions are poorly quantified. Laboratory tests were conducted to measure emissions from startups using kerosene, plastic bags, newspaper, fabric, food packaging, rubber tire tubes, leaves/twigs, footwear, and wood shims. Measured pollutants included: fine particulate matter mass (PM_{2.5}), PM_{2.5} elemental and organic carbon, methane, carbon monoxide, carbon dioxide, benzene, and formaldehyde. Results demonstrate substantial variability in the measured emissions across materials on a per-startup basis. For example, kerosene emitted 496 mg PM_{2.5} and 999 mg CO per startup, whereas plastic bags emitted 2 mg PM_{2.5} and 30 mg CO. When considering emissions on a per-mass basis, the ordering of materials from highest-to-lowest emissions changes, emphasizing the importance of establishing how much material is needed to start a stove. The proportional contribution of startups to overall emissions varies depending on startup material type, stove type, and cooking event length; however, results demonstrate that startup materials can contribute substantially to a cookstove's emissions. Startup material choice is especially important for cleaner stove-fuel combinations where the marginal benefits of reduced emissions are potentially greater.

Graphical Abstract

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Supplemental Information. Additional Methods, Figures, and Tables as referenced in the main text.

Supplemental Information **for Review Only**. Two unpublished citations, as described below.

- Copy of citation #7, which is currently under review: "Fedak, K. M.; Good, N.; Walker, E.; Clark, M. L.; L'Orange, C.; Volckens, J.; Peel, J. L., An Expert Survey on the Material Types used to Start Cookstoves. Energy for Sustainable Development."
- Copy of citation #15, "ISO (International Organization for Standardization) Clean cookstoves and clean cooking solutions - Harmonized laboratory test protocols - Part 3: Voluntary performance targets for cookstoves based on laboratory testing; 2018." This document was approved by the ISO in March and should be available publicly by June 1. A copy of the technical report was provided to by technical report coauthor Christian L'Orange.

Keywords

household air pollution; kerosene; trash burning; biomass; combustion

1. Introduction

Exposure to household air pollution generated by residential burning of solid fuel is a top-ten risk factor for disease globally.¹ These exposures contributed to approximately 77 million disability-adjusted life years in 2016, including over 2.5 million premature deaths.¹ Efforts to reduce the harmful effects of cookstoves have achieved only modest impact,^{2, 3–5} in part because emissions reductions demonstrated in the laboratory have not translated to the real world.⁶ One important source of uncertainty in cookstove emissions/exposures is the contribution from cookstove startup (i.e., the act of igniting a stove).

A range of materials, such as newspaper, plastics, and agricultural wastes, are used to ignite cookstoves.⁷ The composition of these materials differs from main cooking fuels (e.g., wood, charcoal); thus, the emission profiles (and potential health impacts) from these materials may also differ from cooking fuels. Yet, only one study was identified that compared emissions from lighting stoves with different startup materials; this study compared only PM_{2.5} emissions from kerosene and plant stalks.⁸ Several studies have noted the contribution of stove ignition to overall cooking emissions. For example, Carter et al.⁹ reported that lighting contributed to 34–45% of overall PM_{2.5} emissions among Chinese gasifier stoves. Bhattacharya et al.¹⁰ demonstrated that lighting a stove with kerosene-soaked kindling from the top of the fuel bed (versus the bottom) resulted in decreased emissions of carbon monoxide and nitric oxides. Similarly, Lask and Gadgil¹¹ showed that using a ‘lighting cone’ with charcoal stoves reduced emissions of ultrafine particles and carbon monoxide. Yet, no studies to date have systematically isolated startup emissions as a function of startup material type.¹² Most laboratory studies report using kerosene or highly-processed wood shims to ignite stoves, but these materials represent only a fraction of real-world startup materials.¹²

Previously, we surveyed experts about materials used to start cookstoves.⁷ The survey identified eight common materials: accelerants (e.g., kerosene, waxes), plastic (e.g., plastic bags, packaging), paper, kindling, agricultural wastes, high-resin woods (e.g., ocote, pine), fabric scraps, and rubber (e.g., tires, footwear). We characterized emissions from these materials in a laboratory-based study. We developed a protocol to replicate real-world startup events while simultaneously isolating emissions from the startup material. We measured emissions of particulate matter mass less than 2.5 microns in aerodynamic

diameter ($PM_{2.5}$), $PM_{2.5}$ elemental and organic carbon (EC, OC), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), various carbonyls (including formaldehyde and acetaldehyde), and benzene, toluene, ethylbenzene, and xylenes (collectively, 'BTEX').

2. Materials and Methods

2.1. Experimental setup

Tests were performed within a total-capture, constant-volume dilution hood. Particulate and gas sampling probes operated at isokinetic flowrates were located at the duct centerline, from 1-3 m downstream of the hood plenum. The experimental setup is shown in Figure S1.

2.2. Emissions measurements

Carbon dioxide, CO, and CH_4 were measured at 1 Hz using nondispersive infrared detection (Siemens Ultramat 6E, Siemens AG, Germany). $PM_{2.5}$ was measured gravimetrically. Elemental and organic carbon were measured offline using an OCEC Analyzer (Sunset Laboratory, OR, USA).^{13, 14} Select carbonyl compounds were collected on 2,4-dinitrophenylhydrazine cartridges and analyzed offline using high-performance liquid chromatography with ultraviolet detection. Whole air samples were analyzed offline for BTEX using gas chromatography/mass spectrometry. More details are provided in the Supporting Information.

2.3. Material types and preparation

Materials tested included: laboratory-grade kerosene, plastic grocery bags, foil-lined food packaging, newspaper, dry kindling material, bicycle inner tubes, synthetic foam-based footwear, and fabric (Table 1). Additionally, we tested wood shims because they are often used in laboratory tests to ignite stoves (as is kerosene). Materials were prepared into pieces of roughly uniform size, shape, and composition. Materials were sized to represent how they would be used in a real-world situation. For example, rather than cutting the bags or packaging into small pieces, we kept the materials in their natural units (e.g., whole bags or wrappers).

2.4. Test protocol

Materials were burned in a metal, non-insulated stove with an L-shaped combustion chamber ($9.5 \times 17 \times 21$ cm), chosen to mimic the combustion chamber of a simple rocket-elbow stove. Pilot tests were conducted to determine the quantity of each startup material that fit in the stove opening and the number of replicate startup events needed to achieve quantification limits for gravimetric $PM_{2.5}$ analysis. The test protocol involved conducting multiple startup events over a 20 to 30 minute period. Pre-weighed bundles of startup material were ignited in the stove using a single match and burned until no longer visibly smoldering or until CO levels were below 4 ppm (whichever occurred first). Remaining material and ash were removed from the stove and weighed. This process was repeated two to seven times per test, dependent on the material type (Table S1). No main fuel was present in the stove, to allow for the isolation of emissions from the startup material only. Samplers for offline analysis were run continuously throughout the test. Background tests were conducted by running all sampling instruments for 20 minutes without burning a startup

material, randomly in the test sequence once per test day. Additionally, CO₂, CO, and CH₄ were measured 10-minutes pre- and post-test.

We conducted the tests in random order. Each material was assigned to be tested three times. Additional tests were conducted following deviations from the test protocol, instrument errors, or suspected higher-than-normal background levels (based on concurrent activity in the laboratory).

2.5. Analysis

Data processing and analysis were conducted using R (version 3.3.1, The R Foundation for Statistical Computing). Offline measurements were background corrected by subtracting the study-average background values. Time-resolved data (CO₂, CO, and CH₄) were background corrected using the 10-minute pre-/post-test average mixing ratio. Per-startup emissions factors (mg pollutant/startup) were determined by dividing the total emissions per test (which contained multiple startup events) by the number of startup events for that test. The number of startup events per test was calculated on a mass basis (total mass of material burned within test divided by the average mass of a startup bundle for that material type [Table 1]). We then averaged per-startup emissions factors across multiple test replicates. The resulting unit of mean emissions per startup provides an estimate of how much emissions would be expected from a single cookstove startup event. Coefficients of variation (COVs) were calculated as the standard deviation divided by the mean (presented as a percentage) for each material type. We also calculated the mass of pollutant emitted per unit mass of material burned (calculated for each test, which contained multiple startup events, then averaged across test replicates). Modified combustion efficiency (MCE), a metric that indicates the completeness of combustion, was calculated for each test as the ratio of emitted CO₂ divided by the sum of emitted CO and CO₂.

We estimated the contribution of startup materials to the overall emissions of several representative stove technologies that operate across International Organization for Standardization (ISO) Performance Tiers.¹⁵ ISO Tier limits are defined by the mass of CO and PM emitted per unit energy delivered to the cooking vessel (mg/MJ_{delivered}). We defined the emissions for each stove as reported by Jetter et al.¹⁶ and the Global Alliance for Clean Cooking.¹⁷ We defined the energy needs of a cooking event as 1.67 MJ_{delivered} (approximately equivalent to bringing five liters of water from 20°C to 100°C). This was chosen because five liters can be accommodated by most cookstove styles and represents a cooking activity that is commonplace around the world. This procedure also mimics the process used for many laboratory stove testing protocols, including the Water Boiling Test, which are the source of data that underpins the ISO Tiers and is how the emissions factors were derived in Jetter et al.¹⁶ We added the emissions per startup to each stove's emissions per cooking event, assuming one startup occurs per cooking event. We assumed the startup material does not contribute to the energy delivered and that the stove type does not change combustion efficiency of the startup.

3. Results

3.1. Test characteristics

At least three tests were completed per material, with two to seven startup events per test (Tables 1 and S1). One additional test was conducted for kerosene, fabric, and food packaging and two additional tests were conducted for newspaper (resulting in 32 tests across the nine materials). Reasons for additional tests included missing carbonyl data for one kerosene and one newspaper test, missing BTEX data for one fabric test, and concerns over potentially higher background levels in one newspaper and one food packaging test due to concurrent activity in the laboratory. However, background CO and CO₂ levels for these tests were consistent with the expected background levels. As a result, no tests or specific pollutant data were removed from the dataset prior to analysis.

3.2. Emissions per Startup Event

Mean emissions per startup (average value across all tests) are shown in Table 2 (additional carbonyl compounds are provided in Table S2 and emissions as mass of pollutant per unit mass material provided in Table S3). Emissions by test replicate are shown in Figure 1 for several key pollutants (PM_{2.5}, CO, benzene, toluene, formaldehyde, acetaldehyde, EC, and OC). Emissions were consistent across replicates for most materials and pollutants. Coefficients of variation were less than 25% for 36 of the 54 key pollutant/material combinations. The average COV across materials was 31% for acetaldehyde and benzene, 29% for toluene, 19% for CO, and 12% for formaldehyde. PM_{2.5} mass had a COV of 56% across materials but was <35% for all materials except footwear, food packaging, and plastic bags.

PM_{2.5} emissions varied from an average of 2 mg/startup for plastic bags to 496 mg/startup average for kerosene (see Figure 1, Table 2). Kindling (355 mg/startup), footwear (224 mg/startup), inner tubes (151 mg/startup), and newspaper (127 mg/startup) also had relatively high PM_{2.5} emissions. Emissions of PM_{2.5} were lower for wood shims (45 mg/startup), fabric (14 mg/startup), food packaging (8 mg/startup), and plastic bags (2 mg/startup).

A summary of fine particle emissions is provided in Figure 2. The highest EC and OC emissions were for kerosene (181 mg EC/startup and 238 mg OC/startup). Elemental carbon emissions from other materials were below 80 mg/startup (footwear: 77 mg/startup; inner tubes: 69 mg/startup; kindling, newspaper, and wood shims: 8 mg/startup; food packaging: 5 mg/startup; fabric: 2 mg/startup; plastic bags: below background). Similarly, OC values were high for kindling (212 mg/startup) in addition to kerosene, but lower for other materials (newspaper: 73 mg/startup; inner tubes: 60 mg/startup; wood shims: 28 mg/startup; fabric and plastic bags: 5 mg/startup; footwear: 4 mg/startup; food packaging: 1 mg/startup). As seen in Figure 2, the relative contribution of EC and OC to overall emissions varied considerably; for kerosene the ratio of EC to OC was 0.76 and the ratio of EC to total PM_{2.5} mass was 0.36. Emissions of OC were more dominant for wood shims, kindling, newspaper, and fabric resulting in EC to OC ratios of less than 1 (0.29, 0.04, 0.10, and 0.40, respectively) and very low EC to total PM_{2.5} mass ratios (0.18, 0.02, 0.06, and 0.14, respectively). Conversely, EC fractions were greater than OC fractions for footwear, food

packaging, and inner tubes (EC to OC ratios of 19.25, 5.0, and 1.15, respectively); EC to $PM_{2.5}$ mass ratios were also higher for these materials (0.34, 0.625, and 0.46, respectively). Assuming the organic mass to organic carbon ratio is in the 1.2 to 1.5 range,^{18, 19} carbonaceous particles account for close to 100% of the $PM_{2.5}$ mass emitted from all materials (Figure S5 and S6). Any non-speciated $PM_{2.5}$ mass is likely comprised of ionic compounds.^{18, 19}

Carbon monoxide emissions ranged from 30 mg/startup for plastic bags to 999 mg/startup for kerosene. Emissions of CO were more dichotomized across materials than $PM_{2.5}$ emissions. Plastic bags, inner tubes, footwear, fabric, and food packaging emitted less than 150 mg/startup for any given test, whereas kerosene, kindling, newspaper, and wood shims emitted 319 to 1000 mg/startup. Average CO emissions were highest for kerosene and kindling (488 and 999 mg/startup, respectively) and lower for fabric, food packaging, and plastic bags (58, 46, and 30 mg/startup, respectively). However, CO emissions were also low for footwear (45 mg/startup) despite higher $PM_{2.5}$ emissions for this material.

Total BTEX emissions followed a similar trend as CO in that they are highest for kerosene, kindling, and newspaper, whereas inner tubes, fabric, food packaging, footwear, and plastic bags have relatively lower BTEX emissions (Figure 3). Kerosene produced the highest total BTEX emissions (28.11 mg/startup, driven primarily by higher benzene at 18.5 mg/startup). Kindling had the second highest (15.9 mg/startup) followed by newspaper (10.2 mg/startup). Other materials emitted 4 mg/startup total BTEX or less. Benzene accounted for 50% or more of total BTEX emissions for all materials except footwear (newspaper: 76% inner tubes: 72%, kerosene: 66%, fabric: 58%, kindling: 54%, food packaging: 51%, plastic bags: 50%, footwear: 23%). Toluene accounted for 13-26% of total BTEX emissions (kindling and wood shims: 26%, footwear: 23%, plastic bags: 20%, fabric: 19%, food packaging: 18%, newspaper: 16%, inner tubes: 14%, kerosene: 13%). Ethylbenzene was less than 10% of BTEX emissions for all materials. Though no pattern is seen for BTEX emissions across materials, similarities are apparent for wood shims and kindling (both wood-based materials): total BTEX emissions were around 54% benzene, 26% toluene, and 13 to 15% xylenes. Plastic bags and food packaging (both thin plastic materials) also had a similar compositional breakdown: approximately 50% benzene, 20% toluene, 25% xylene, and 5-6% ethylbenzene. Finally, newspaper and inner tubes were similar: approximately 75% benzene, 15% toluene, and 2-3% ethylbenzene, though with varying xylene (12% for inner tubes versus only 5% for newspaper). Differences in the BTEX compositions were mainly driven by changes in the benzene to toluene ratio, which ranged from 1.0 to 5.2 across the different material types (kerosene: 5.2, inner tubes: 5.0, newspaper: 4.7, fabric: 3.1, food packaging: 2.8, plastic bags 2.5, kindling: 2.1, footwear: 1.0).

Acetaldehyde and formaldehyde emissions were higher for kindling than all other startup materials tested (acetaldehyde: 17.6 mg/startup, formaldehyde: 26.9 mg/startup). Other materials generally emitted less than a quarter of the amount of acetaldehyde and less than one third the amount of formaldehyde as kindling (with the exception of formaldehyde emissions from newspaper, which were about two-thirds the amount emitted from kindling). The next highest emitting materials included wood shims (acetaldehyde: 4.4 mg/startup, formaldehyde: 8.3 mg/startup), newspaper (acetaldehyde: 3.8 mg/startup, formaldehyde:

17.1 mg/startup), and kerosene (acetaldehyde: 2.2 mg/startup, formaldehyde: 4.8 mg/startup). Acetaldehyde emissions from all other materials were around 1 mg/startup or less (fabric: 1.1, food packaging: 0.9, plastic bags, footwear and inner tubes: 0.6). Formaldehyde emissions from all other materials were between 1-1.7 mg/startup (inner tubes and fabric: 1.7, footwear: 1.3, food packaging and plastic bags: 1.1).

3.3. Emissions on per-mass basis

Emissions on a per-mass basis are presented in Table S3 and Figures S2, S3, and S4. The ordering of materials from highest-to-lowest emissions changes when considering emissions in this unit compared to a per-startup basis (Figure 1 vs. Figure S2), emphasizing the impact of the different mass of material needed for each startup event depending on the material type. An overall trend is maintained, however, wherein kerosene, kindling, and sometimes newspaper appear among the higher-emitting materials for non-CO₂ pollutants (e.g., PM_{2.5}, CO, BTEX, and carbonyls) while plastic bags, food packaging, and fabric emit less of the non-CO₂ pollutants.

3.4. Modified Combustion Efficiencies

Mean MCEs ranged from 0.93 (kindling) to >0.99 (footwear, food packaging) (see Table S4). MCE within a single startup event peaked quickly then tapered towards the end. The range of MCEs for a single test were low and within the range of predominantly flaming combustion. Mean 5th percentile values were lowest for newspaper and kindling (0.86 each) but above 0.90 for all other materials. Mean 95th percentile values ranged from 0.98 to >0.99 across all materials.

3.5. Impact of Startup Emissions on ISO Tiers

The implications of adding a startup event to a stove's overall emissions are illustrated in Figure 4. For each stove, addition of a startup using plastic bags (the lowest-emitting material studied) does not change the stove's Tier rating. However, a kerosene startup (the highest-emitting material studied) results in certain stoves shifting Tiers. For relatively "cleaner" cookstoves (Tiers 3 through 5), the contribution from a startup material to overall emissions is large proportional to the emissions from the cooking event. The limit values for Tiers 3-5 are narrow, so shifts from one tier to the next can happen with only a small change in emissions (owing to the nonlinear tier spacing). The addition of the kerosene startup therefore shifts these stoves into "dirtier" Tiers. For example, the Mimi Moto gasifier shifts from Tier 4 to Tier 1 when accounting for a kerosene startup. Within the higher-emissions Tiers (Tier 0, 1, and 2), the contribution of a startup, regardless of startup material choice, is smaller compared to the emissions from the stove and the tier limits are wider. As a result, the shifts are less drastic. For example, the Berkeley Darfur and Protos stoves each shift one tier, whereas the Envirofit G-3300 stays within Tier 1 (shifting from the lowest end of the Tier to the highest limit).

4. Discussion

Results demonstrate that emissions profiles vary across startup materials, likely due to a combination of factors. For example, different material shape and chemical composition

likely effect both the rate and efficiency of combustion, leading to differential emissions. Further, the mass of a given material needed to complete a startup event also plays a role in overall emissions, regardless of combustion efficiency (i.e., 1.8 g of plastic bags vs. 17.6 g of wood shims). Kerosene and kindling demonstrated consistently high emissions across multiple pollutants on a per-startup basis – often an order of magnitude higher than other materials. Newspaper and wood shims were also consistently among the highest emitters of the pollutants measured. Plastic bags were the lowest-polluting choice of the materials studied across nearly every pollutant measured. Food packaging and fabric were also consistently lower emitters. Kerosene is a very common fire starter used globally and also used as a main fuel in some advanced stove designs. Our data indicates that, of the materials characterized, kerosene is the highest emitted of the pollutants measured on a per-startup basis.

4.1 Implications of startup material emissions on overall cookstove emissions and exposures

The use of startup materials adds to the emissions for all cookstoves, shifting towards higher total emissions from a cooking event. However, the extent to which this shift matters depends on the base emissions from the main cooking event. For example, emissions from a main cooking event using wood fuels in a three stone fire are estimated to be on the order of 0.5-1 g PM_{2.5} per liter of water boiled per hour; emissions from a more advanced wood-burning gasifier are lower, around 0.03 g/liter-hour for PM_{2.5}.¹⁶ For a simple cooking event such as an hour of simmering one liter volume of water or food, a kerosene startup (at approximately 0.5 g of PM_{2.5}) would contribute 33 to 50% of total PM_{2.5} emissions from a three stone fire, yet 94% of total PM_{2.5} emissions from a gasifier. Conversely, a low-emitting startup material such as plastic bags, which registered approximately 0.002 g PM_{2.5} per startup event, would only contribute to less than 1% of total PM_{2.5} emissions from a three-stone fire and around 5% of PM_{2.5} emissions from a gasifier. Notably, some stoves are not ignited every time a cooking event occurs; instead, they may be ignited once and then remain lit throughout a full day or longer. Additionally, factors such as fuel type, fuel moisture content, cooking practices, and stove condition can affect the main stove emissions in real-world settings. Impact assessments should consider how the startup contributes under different stove use patterns for a more accurate comparison of total emissions across stoves.

An additional consideration, however, is that evidence suggests PM-associated health effects from cookstove air pollution exposures may be supralinear: greater changes in relative health risks occur with increases in exposure at lower exposure levels than with the same increases at higher starting exposure levels.^{20, 21} The 2018 ISO Cookstove Performance Tiers reflect this supralinear health relationship, with lower-emission Tiers occupying a tighter distribution than the higher-emission Tiers.¹⁵ Considering how a startup event impacts total emissions for a cooking event within this Tier system, our results illustrate that the differences in emissions across different startup materials may be most important from a health perspective when considering lower-emission/higher-performance Tier stoves. The emissions differences across startup materials become less important in the lower-performance Tiers, where the base emissions from the main cooking event are higher (so

differences in emissions from one startup material to another are proportionally less meaningful to the overall emissions).

We measured emissions from the startup combustion, not exposure. To draw conclusions about the health impact of startups, further work is needed to translate emissions factors to estimated indoor air concentrations and subsequent exposure levels. While relative differences in emissions can be expected to roughly translate to relative differences in exposure, there are several factors that could result in a disconnect across different startup materials. For example, behavioral aspects such as how the cook interacts with the stove and startup material during the ignition process could change combustion dynamics or impact breathing.

4.2 Metrics for emissions: per startup vs. mass burned

We standardized emissions to “per-startup” units to approximate real-world lighting emissions in a way that does not depend on differing burn rates and densities of startup materials. Relative differences in emissions on a per-startup basis can be reasonably expected to translate to relative differences in exposure and therefore health risks.

Emissions factors on a mass basis (grams pollutant emitted per kilogram material burned, as shown in Table S3 and Figures S2 and S3) allow the emissions reported here to be related to other combustion applications, such as military waste burning or residential trash burning in backyard burn pits. When considering emissions in these units, the differences across materials changes drastically from what is seen on a per-startup basis. Emissions of the measured pollutants become more similar between different startup materials. Emissions from kerosene, wood shims, kindling, and newspaper (which were relatively high across multiple pollutants on a per-startup basis) appear within the same range as emissions from fabric, plastic bags, food packaging, inner tubes, and footwear (relatively low on a per-startup basis). This emphasizes that the choice to compare emissions across multiple materials on a per-startup basis drives conclusions that depend on comparisons across materials and is therefore integral to the extrapolation of these laboratory-based findings to real-world settings.

Few reports exist detailing emissions from startup materials that are comparable to this study. Our measured emissions for CO, CO₂, methane, formaldehyde, benzene, EC (black carbon), and OC are all within an order of magnitude of those reported for open waste burning by Wiedenmyer et al.²² The composition of open waste is undefined but presumably mixed material types; our emission factors could help refine estimates for certain types of waste. Additionally, some comparisons can be drawn between emissions from startup materials and general cookstove emissions factors. Our emission estimates for wood shim startups (g/kg CO: 24; PM_{2.5}: 3; benzene: 0.12; toluene: 0.06; acetaldehyde: 0.25; formaldehyde: 0.47) are in line with reported emissions from wood-burning cookstoves (g/kg CO: 17-60; PM_{2.5}: <10; benzene: 0.1-2.5; toluene: <0.5; acetaldehyde: 0.1-0.8; formaldehyde: 0.2-1.7).²³⁻²⁶ Studies of kerosene wick stoves cover a wide range of PM_{2.5} emissions (from 0.29 to 124 g/kg^{26, 27}), potentially due to differences in stove type and operating conditions.²⁷ Our estimates (32 g/kg) are in line with higher estimates from other research. Similarly, CO emission estimates for kerosene-burning cookstoves vary from very

low (2.8 g/kg²³) to within the range of our kerosene startup estimates (31 g/kg, compared to 11-21 g/kg²⁷ or 27 g/kg²⁶).

Few studies have reported on carcinogenic emissions (e.g., benzene, acetaldehyde, formaldehyde) from cookstoves or biomass fuels. Our results indicate that these carcinogens are emitted from startup materials at levels that are important to human health compared to the main cooking event. For example, Zhang and Smith²⁸ report emissions of carbonyls from cookstoves burning different main fuel types (wood, coal, kerosene, and LPG) where acetaldehyde emissions were 0.02-0.17 g/kg and formaldehyde emissions were 0.02 to 0.14 g/kg. Our emissions factors were higher (acetaldehyde: 0.09-0.88 g/kg; formaldehyde: 0.19 to 0.91 g/kg). On a per-startup basis, acetaldehyde emissions ranged from approximately 0.5-18 g/startup for acetaldehyde and 1-27 g/startup for formaldehyde. Various reports indicate emissions from biomass burning range from <0.1 to 2.5 g/kg for benzene and 0.02 to 0.18 g/kg for toluene.^{25, 29-31} These values are aligned with emissions from our startups (0.05-1.18 g/kg benzene, 0.05-0.23 g/kg toluene); which translate to per-startup emissions that can reach several grams.

4.3 Other strengths and limitations

We replicated aspects of real-world startups by burning small bundles of material within a generic stove. We expect test-to-test variability in emissions due to the inherent variability in cookstove combustion and the startup process that the experiments were designed to capture. The COVs showed 12 to 56% variability between tests, dependent on the pollutant. However, there may be other contributors to variability in real-world emissions that we did not capture in our protocol. Startup material composition and quantity may be more variable than we captured. For example, the kindling startup material we tested was comprised of twigs, grasses, and weeds sourced from northern Colorado; kindling materials used to start cookstoves around the world can be highly varied across different regions based on the local flora.

We chose to burn the startup material only, without a main fuel bed. This was beneficial for isolating the emissions from just that startup material and ensuring that our integrated measurements did not capture any emissions from the main fuel, which would be harder to control across test replicates. Additionally, not all startup materials are appropriate for use with all fuel types, making selection of a consistent main fuel difficult. However, the burning dynamics of the startup material could be different when integrated with a main fuel type (for example, if the heating of a fuel bed under the startup material impacts the burn temperatures or airflow dynamics across the startup material). We observed predominately flaming combustion (mean MCE: 93-99%), which is desired when attempting to ignite fuel; different combustion conditions could lead to different emissions. Further research is needed to quantify the impact of interactions between startup, main fuel, and stove type on emissions.

Our study is limited in that we only tested a subset of startup materials that are used globally. A recent survey conducted by our group indicated that a wide variety of different materials are used to start stoves around the world, however those materials could reasonably be categorized into eight main groups of commonly used material types.⁷ The

emissions data reported here cover the most common categories (accelerants [kerosene], plastics [plastic bags], paper [newspaper], kindling, rubber/rubber-like materials [inner tubes, footwear], and fabric). We additionally tested food packaging/wrappers as these materials as well as household trash in general were noted, though less commonly, within the survey. While our selection of materials covers a range of startup materials globally, there could still be additional variation in emissions expected due to inherent variability in material types within these groupings. For example, plastic bags may not be representative of other types of plastic-based materials used during startup, such as plastic packaging/wrappings or plastic bottles. We did not test agricultural waste and high-resin pine woods (the remaining two of the eight common material type groups that emerged from the survey results) due to cost constraints and logistical challenges in procuring these materials. Emissions from these materials may be important to consider from health and climate perspectives, similar to the materials tested in this study, and should be included in future work.

Our study was more comprehensive than many previous laboratory emissions studies in the pollutant types characterized, including particulate matter characteristics, carbon gases, volatile organic compounds, and carbonyls. However, combustion emissions are a complex mixture and we did not measure all classes of pollutants expected to be emitted. For example, we did not measure dioxin and dioxin-like compounds or polychlorinated biphenyls. These highly toxic compounds are known to be emitted from burning halogenated plastics and papers,^{32–34} so may be relevant for some startup material types. Some classes of unmeasured pollutants may follow different trends across the material types than the trends seen in our measured pollutants, which would impact conclusions about the overall health risks associated with different material types.

Previous studies aimed at understanding cookstove emissions as a whole have characterized emissions from the stove startup phase.^{9, 10, 11} These studies predominately use kerosene or wood shims to ignite the main fuel and focus on understanding emissions from the ignition phase – the first minutes of the main fuel burning after it has been ignited with aid from the startup material – as opposed to understanding the emissions coming from the startup material. Other studies have noted the use of different materials to start cookstoves in the field, such as newspaper, kindling, lighter fluid, or cow dung,^{6, 35} yet have not characterized how these different materials relate to measured emissions. To our knowledge, this is the first study to isolate and characterize pollutants emitted from a variety of real-world relevant cookstove startup materials.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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ABBREVIATIONS:

PM_{2.5}	particulate mass less than 2.5 microns in aerodynamic diameter
CO	carbon monoxide
CO₂	carbon dioxide
EC	elemental carbon
OC	organic carbon
MCE	modified combustion efficiency
VOC	volatile organic compound
BTEX	benzene, toluene, ethylbenzene, and xylenes
COV	coefficient of variation

Citations

1. GBD 2016 Risk Factors Collaborators, Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. *Lancet* 2017, 390, (10100), 1345–1422. [PubMed: 28919119]
2. Clark M; Bachand AM; Heiderscheidt JM; Yoder SA; Luna B; Volckens J; Koehler KA; Conway S; Reynolds SJ; Peel JL, Impact of a cleaner-burning cookstove intervention on blood pressure in Nicaraguan women. *Indoor Air* 2013, 23, (2), 105–14. [PubMed: 22913364]
3. McCracken J; Smith KR; Stone P; Diaz A; Arana B; Schwartz J, Intervention to Lower Household Woodsmoke Exposure in Guatemala Reduces ST-segment Depression on Electrocardiograms. *Environ. Health Perspect* 2011, 119, 1562–1568. [PubMed: 21669557]
4. McCracken JP; Smith KR; Diaz A; Mittleman MA; Schwartz J, Chimney stove intervention to reduce long-term wood smoke exposure lowers blood pressure among Guatemalan women. *Environ. Health Perspect* 2007, 115 (7), 996–1001. [PubMed: 17637912]
5. Alexander D; Northcross A; Wilson N; Dutta A; Pandya R; Ibigbami T; Adu D; Olamijulo J; Morhason-Bello O; Karrison T; Ojengbede O; Olopade CO, Randomized Controlled Ethanol Cookstove Intervention and Blood Pressure in Pregnant Nigerian Women. *Am. J. Respir. Crit. Care Med* 2017, 195 (12), 1629–1639. [PubMed: 28081369]
6. Roden CA; Bond TC; Conway S; Osorto Pinel AB; MacCarty N; Still D, Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. *Atmos. Environ* 2009, 43 (6), 1170–1181.
7. Fedak KM; Good N; Walker E; Clark ML; L'Orange C; Volckens J; Peel JL, An Expert Survey on the Material Types used to Start Cookstoves. *Energy Sustain. Dev Under Review*.
8. Arora P; Das P; Jain S; Kishore VVN, A laboratory based comparative study of Indian biomass cookstove testing protocol and Water Boiling Test. *Energy Sustain. Dev* 2014, 21, 81–88.
9. Carter EM; Shan M; Yang X; Li J; Baumgartner J, Pollutant emissions and energy efficiency of Chinese gasifier cooking stoves and implications for future intervention studies. *Environ. Sci. Tech* 2014, 48 (11), 6461–7.
10. Bhattacharya SC; Albina DO; Myint Khaing A, Effects of selected parameters on performance and emission of biomass-fired cookstoves. *Biomass and Bioenergy* 2002, 23 (5), 387–395.
11. Lask K; Gadgil A, Performance and emissions characteristics of a lighting cone for charcoal stoves. *Energy Sustain. Dev* 2017, 36, 64–67.
12. Arora P; Jain S, A review of chronological development in cookstove assessment methods: Challenges and way forward. *Renewable and Sustainable Energy Reviews* 2016, 55, 203–220.

13. Maimone F; Turpin BJ; Solomon P; Meng Q; Robinson AL; Subramanian R; Polidori A, Correction Methods for Organic Carbon Artifacts When Using Quartz-Fiber Filters in Large Particulate Matter Monitoring Networks: The Regression Method and Other Options. *J. Air Waste Manage. Assoc* 2011, 61 (6), 696–710.
14. Subramanian R; Khlystov AY; Cabada JC; Robinson AL, Positive and Negative Artifacts in Particulate Organic Carbon Measurements with Denuded and Undenuded Sampler Configurations Special Issue of Aerosol Science and Technology on Findings from the Fine Particulate Matter Supersites Program. *Aerosol Sci. Technol* 2004, 38, (sup1), 27–48.
15. ISO (International Organization for Standardization) Clean cookstoves and clean cooking solutions - Harmonized laboratory test protocols - Part 3: Voluntary performance targets for cookstoves based on laboratory testing; 2018.
16. Jetter J; Zhao Y; Smith KR; Khan B; Yelverton T; DeCarlo P; Hays MD, Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards. *Environ. Sci. Tech* 2012, 46 (19), 10827–10834.
17. Global Alliance for Clean Cookstoves Clean Cooking Catalog: Product and Performance Data for the Cookstove Sector. <http://catalog.cleancookstoves.org/stoves> (4 2018).
18. Turpin BJ; Lim H-J, Species Contributions to PM_{2.5} Mass Concentrations: Revisiting Common Assumptions for Estimating Organic Mass. *Aerosol Sci. Technol* 2001, 35 (1), 602–610.
19. Reece SM; Sinha A; Grieshop AP, Primary and Photochemically Aged Aerosol Emissions from Biomass Cookstoves: Chemical and Physical Characterization. *Environ. Sci. Tech* 2017, 51 (16), 9379–9390.
20. Burnett RT; Pope CA 3rd; Ezzati M; Olives C; Lim SS; Mehta S; Shin HH; Singh G; Hubbell B; Brauer M; Anderson HR; Smith KR; Balmes JR; Bruce NG; Kan H; Laden F; Pruss-Ustun A; Turner MC; Gapstur SM; Diver WR; Cohen A, An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect* 2014, 122 (4), 397–403. [PubMed: 24518036]
21. Smith KR; Peel JL, Mind the gap. *Environ. Health Perspect* 2010, 118 (12), 1643–5. [PubMed: 20729177]
22. Wiedinmyer C; Yokelson RJ; Gullett BK, Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste. *Environ. Sci. Tech* 2014, 48 (16), 9523–9530.
23. Chen LWA; Moosmüller H; Arnott WP; Chow JC; Watson JG; Susott RA; Babbitt RE; Wold CE; Lincoln EN; Hao WM, Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and Source Profiles. *Environ. Sci. Tech* 2007, 41 (12), 4317–4325.
24. Christian TJ; Yokelson RJ; Cárdenas B; Molina LT; Engling G; Hsu SC, Trace gas and particle emissions from domestic and industrial biofuel use and garbage burning in central Mexico. *Atmospheric Chem. Phys* 2010, 10 (2), 565–584.
25. Stockwell C; Veres P; Williams J; Yokelson R, Characterization of biomass burning emissions from cooking fires, peat, crop residue, and other fuels with high-resolution proton-transfer-reaction time-of-flight mass spectrometry. *Atmospheric Chem. Phys* 2015, 15 (2), 845–865.
26. World Health Organization Indoor Air Quality Guidelines: Household fuel Combustion - Review 2: Emissions of Health-Damaging Pollutants from Household Stoves. <http://www.who.int/indoorair/guidelines/hhfc/evidence/en/>
27. Lam NL; Chen Y; Weyant C; Venkataraman C; Sadavarte P; Johnson MA; Smith KR; Brem BT; Arineitwe J; Ellis JE; Bond TC, Household Light Makes Global Heat: High Black Carbon Emissions From Kerosene Wick Lamps. *Environ. Sci. Tech* 2012, 46 (24), 13531–13538.
28. Zhang J; Smith KR, Emissions of carbonyl compounds from various cookstoves in China. *Environ. Sci. Tech* 1999, 33 (14), 2311–2320.
29. Yokelson RJ; Burling I; Gilman J; Warneke C; Stockwell C; Gouw J. d.; Akagi S; Urbanski S; Veres P; Roberts J, Coupling field and laboratory measurements to estimate the emission factors of identified and unidentified trace gases for prescribed fires. *Atmospheric Chem. Phys* 2013, 13 (1), 89–116.

30. Tawfiq MF; Aroua MK; Sulaiman NMN, On-line CO, CO₂ emissions evaluation and (benzene, toluene, xylene) determination from experimental burn of tropical biomass. *J. Environ. Sci* 2015, 33, 239–244.
31. Akagi S; Yokelson RJ; Wiedinmyer C; Alvarado M; Reid J; Karl T; Crounse J; Wennberg P, Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmospheric Chem. Phys* 2011, 11 (9), 4039–4072.
32. Verma R; Vinoda KS; Papireddy M; Gowda ANS, Toxic Pollutants from Plastic Waste- A Review. *Procedia Environ. Sci* 2016, 35, (Supplement C), 701–708.
33. Zhang M; Buekens A; Jiang X; Li X, Dioxins and polyvinylchloride in combustion and fires. *Waste Manag. Res* 2015, 33 (7), 630–43. [PubMed: 26185164]
34. Hu M-T; Chen S-J; Huang K-L; Lin Y-C; Chang-Chien G-P; Tsai J-H, Characterization of polychlorinated dibenzo-p-dioxin/dibenzofuran emissions from joss paper burned in a furnace with air pollution control devices. *Sci. Total Environ* 2009, 407 (10), 3290–3294. [PubMed: 19232680]
35. Dutta K; Shields KN; Edwards R; Smith KR, Impact of improved biomass cookstoves on indoor air quality near Pune, India. *Energy Sustain. Dev* 2007, 11, (2), 19–32.

Figure 1.

Emissions (mg) per startup event for select pollutants. Each circle represents the calculated average emissions per startup event for an individual test. Materials are ordered from left to right by highest to lowest emissions of PM_{2.5} mass.

Figure 2. Emissions of fine particulate mass (PM_{2.5}; light grey bars), elemental carbon (EC; dark grey bars), and organic carbon (OC; green bars) for different startup materials. Emissions in milligrams of pollutant per startup event. Inset highlights results for lower-emitting materials. The lighter grey bar shows PM_{2.5} footwear emissions with the outlier included.

Figure 3. Comparison of the relative composition of BTEX emitted across different startup materials.

Emissions in milligrams of pollutant per startup event. Inset highlights results for lower-emitting materials. The stacked bar height represents the total BTEX emissions.

Figure 4. Influence of Startup Material on Cookstove Emissions.

The ISO Tiers for cookstove performance are plotted as ranges of CO and PM_{2.5} emission factors (log scale). Emissions for select stove types^{16, 17} are shown as solid-filled circles; open symbols depict the change in emissions after including the contribution from selected startup materials. For illustrative purposes, arrows demonstrate the magnitude of these effects for the Mimi Moto stove (a low-emissions, Tier 4 gasifier). Calculations assume one startup event for a single 1.67 MJ cooking event (i.e., bringing 5 liters of water to boil at normal temperature and pressure).

Experimental Matrix.

Table 1.

We conducted a total of 39 tests across nine startup fuel types (minimum of three tests per fuel).

Fuel Type	Fuel description	Number of tests	Average fuel mass (g) per startup event (range)	Average burn time (min) per startup event (range)
kerosene	Laboratory grade kerosene (approximately 15 grams/startup)	4	15.7 (14.5, 17.6)	4.0 (2.1, 6.6)
kindling	Dried twigs and leaves from willow oak trees cut into pieces smaller than 8 in long x 2in wide, mixed with small amounts of dried grasses, weeds, and wood shavings (two handful/startup)	3	19.9 (16.2, 25.2)	3.7 (2.9, 4.3)
footwear	Foam flipflop/sandals (ethylene-vinyl acetate [EVA]/rubber composite [*]), cut into pieces approximately 4 in long x 1 in wide (two strips/startup)	3	6.9 (5.0, 8.8)	8.8 (6.5, 10.8)
inner tubes	Used bicycle inner tubes (butyl rubber/latex [*]) cut into pieces approximately 4 in long x 1 in wide (two strips/startup)	3	4.4 (3.3, 5.2)	5.0 (3.6, 6.6)
newspaper	Printed newspaper sheet (appx. 15x22in), crumpled into a ball (two sheets/startup)	5	18.7 (13.6, 24.5)	2.9 (1.9, 4.8)
wood shims	Two wooden shims stapled together with a small wooden separator (one pair/startup)	3	17.6 (11.8, 21.5)	10.2 (7.3, 13.3)
fabric	Plain colored cotton t-shirts (no ink/graphics), cut into pieces approximately 6 in long x 1 in wide (two pieces/startup)	4	2.7 (0.9, 3.5)	2.8 (2.0,4.7)
food packaging	Wrappers (foil-lined polypropylene [*]) from individual-sized snack foods (1-3 wrappers/startup, aim for 10 grams total/test)	4	2.5 (1.1, 4.2)	4.1 (1.8, 6.8)
plastic bags	Brown and white plastic grocery bags (polyethylene [*]) with some ink design, tied in a lose knot (two bags/startup)	3	1.8 (0.7, 2.8)	3.4 (2.2, 4.5)

* material composition is presumed based on online search of material makeup.

Table 2.

Mean Emissions per Startup Event.

Values are background adjusted. n=number of tests, each test contained multiple startup events (2-7, see table S1) to achieve the total number of startups listed across all tests.

	Emissions (mg) Per Startup Event (Average [min, max])								
	kerosene (n=4 tests; 21 total startups)*	kindling (n=3 tests; 9 total startups)	footwear (n=3 tests; 7 total startups)	inner tubes (n=3; 12 total startups)	newsprint (n=5 tests; 33 startups)*	wood shims (n=3 tests; 6 startups)	fabric (n=4 tests; 24 startups)	food packaging (n=4 tests; 23 startups)	plastic bags (n=3 tests; 18 startups)
Carbon Gases									
carbon dioxide	45543 (43663, 47474)	25029 (22622, 26252)	9281 (6857, 13248)	11359 (10875, 12227)	29726 (28572, 30808)	27803 (26723, 28733)	4307 (4197, 4409)	5277 (3706, 8155)	2788 (2174, 3111)
carbon monoxide	488 (477, 499)	999 (939, 1036)	45 (35, 58)	124 (108, 145)	844 (662, 986)	418 (319, 497)	58 (51, 64)	46 (31, 84)	30 (26, 38)
Methane	48 (31, 89)	62 (57, 69)	6 (<BG, 9)	9 (6, 12)	46 (29, 92)	27 (22, 33)	9 (<BG, 36)	27 (<0.5, 109)	1 (<0.5, 3)
Particulate Matter									
PM _{2.5} mass	496 (371, 564)	355 (333, 397)	224 (73, 499 [†])	151 (136, 174)	127 (91, 143)	45 (27, 57)	14 (11, 17)	8 (1, 13)	2 (<BG, 7)
PM _{2.5} EC	181 (80, 293)	8 (6, 12)	77 (58, 89)	69 (61, 83)	8 (4, 12)	8 (2, 12)	2 (<0.5, 3)	5 (<BG, 10)	<BG (<BG, 1)
PM _{2.5} OC	238 (136, 348)	212 (188, 257)	4 (1, 7)	60 (34, 87)	73 (58, 85)	28 (12, 37)	5 (4, 6)	1 (<BG, 3)	5 (3, 7)
Volatile Organic Compounds									
benzene	18.5 (16.9, 20)	8.5 (8, 9.3)	0.3 (0.3, 0.4)	1.8 (1, 3)	7.8 (4, 10.4)	2.2 (1.7, 2.6)	0.7 (0.4, 1.2)	0.7 (0.5, 0.9)	0.3 (0.2, 0.6)
Ethylbenzene	1.4 (1.3, 1.5)	1.1 (1.1, 1.2)	0.1 (<0.1, 0.2)	0.1 (<0.05, 0.1)	0.3 (0.2, 0.5)	0.2 (0.2, 0.3)	0.05 (<0.05, 0.1)	0.1 (0.5, 0.1)	<0.1 (<0.05, 0.1)
m+p xylenes	2.7 (2.5, 3.2)	1.5 (1.5, 1.6)	0.5 (0.3, 0.6)	0.2 (0.1, 0.4)	0.3 (0.2, 0.4)	0.4 (0.3, 0.5)	0.2 (0.1, 0.3)	0.2 (0.1, 0.4)	0.1 (<0.1, 0.1)
o-xylene	1.9 (1.6, 2.2)	0.7 (0.7, 0.7)	0.2 (0.1, 0.3)	0.1 (<0.1, 0.2)	0.1 (0.1, 0.2)	0.2 (0.1, 0.2)	0.1 (0.1, 0.1)	0.1 (0, 0.3)	0.1 (0, 0.1)
toluene	3.6 (3.1, 3.9)	4.1 (4, 4.1)	0.3 (0.2, 0.4)	0.4 (0.3, 0.5)	1.7 (0.9, 2.3)	1.1 (0.9, 1.2)	0.2 (0.1, 0.5)	0.3 (0.2, 0.3)	0.1 (0.1, 0.2)
Carbonyls									
Acetaldehyde	2.2 (2, 2.4)	17.6 (5.2, 24.1)	0.6 (0.6, 0.6)	0.6 (0.4, 1)	3.8 (0.7, 7.1)	4.4 (3.3, 5.2)	1.1 (0.8, 1.3)	0.9 (0.7, 1.1)	0.6 (0.6, 0.7)
Acrolein	<0.05 (<0.1, 0.1)	1.2 (0.9, 1.6)	0.05 (<0.05, 0.1)	<0.05 (<0.05, <0.05)	0.6 (0.2, 0.8)	0.1 (0.1, 0.2)	<0.05 (<0.05, 0.1)	<0.05 (<0.05, <0.05)	<0.05 (<0.05, <0.05)
Formaldehyde	4.8 (4.5, 5.3)	26.9 (20.4, 31.4)	1.3 (1.2, 1.4)	1.7 (1.5, 1.8)	17.1 (15.4, 19)	8.3 (6.4, 9.3)	1.7 (1.6, 1.7)	1.1 (1, 1.4)	1.1 (0.9, 1.2)
Crotonaldehyde	0.2 (0.2, 0.2)	1.5 (0.8, 1.9)	0.1 (<0.05, 0.2)	<0.05 (<0.05, 0.05)	0.4 (0.2, 0.5)	0.4 (0.3, 0.4)	<0.1 (0.05, 0.1)	0.05 (<0.05, 0.1)	0.1 (<0.05, 0.1)

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* Carbonyls had one less n.

The 499 mg/startup PM_{2.5} value is an unexplained outlier, when removed, the average is 86 mg/startup event.

EC = elemental carbon; OC = organic carbon; PM_{2.5} = particulate matter mass less than 2.5 microns in diameter.

<BG = measured concentration was below mean background concentration; therefore, emissions factors could not be calculated.