

Environmental Science Atmospheres

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: O. E. Oghama, A. Voliotis, T. Bannan, S. A. Syafira, D. Hu, H. Wu, P. Gallimore, G. McFiggans, H. Coe and J. Allan, *Environ. Sci.: Atmos.*, 2025, DOI: 10.1039/D5EA00080G.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

Variations in oxygenated and nitrogen-containing primary organic compounds by fuel type and burning condition in stove emissions

View Article Online
DOI: 10.1039/D5EA00080G

Osayomwanbor E. Oghama ^{*a}, Aristedis Voliotis ^{a,b}, Thomas J. Bannan ^a, Sara A. Syafira ^a, Dawei Hu ^a, Huihui Wu ^{a,c}, Peter Gallimore ^a, Gordon McFiggans ^a, Hugh Coe ^{a,b}, James D. Allan ^{*a,b}

Environmental significance statement

Increasing energy prices has led to the proliferation in the use of domestic wood stoves in recent years, and this is projected to rise even further. Across different regions, different biomass fuels are burned to meet residential heating demands. While several studies have attempted to characterise emissions from domestic burners, there are still gaps in knowledge due to the variability in emissions from different biomass fuels and combustion phases. In this study, four different biomass types are burned in a woodstove and the primary emissions are chemically characterised. The results reveal variations in the oxygenated and nitrogen-containing fraction of the emissions by fuel type and burning phase and improve our comprehension of fresh stove emissions. The results also provide a foundation for enhancing our understanding of secondary emissions from biomass burning.



Variations in oxygenated and nitrogen-containing primary organic compounds by fuel type and burning condition in stove emissions

View Article Online
DOI: 10.1039/D5EA00080G

Osayomwanbor E. Oghama ^a, Aristedis Voliotis ^{a,b}, Thomas J. Bannan ^a, Sara A. Syafira ^a, Dawei Hu ^a, Huihui Wu ^{a,c}, Peter Gallimore ^a, Gordon McFiggans ^a, Hugh Coe ^{a,b}, James D. Allan ^{*a,b}

^a Centre for Atmospheric Science (CAS), Department of Earth and Environmental Sciences, University of Manchester, Manchester, M13 9PL, United Kingdom

^b National Centre for Atmospheric Science (NCAS), University of Manchester, Manchester, M13 9PL, United Kingdom

* Email: osayomwanbor.oghama@manchester.ac.uk; james.allan@manchester.ac.uk

Abstract

Biomass burning emits primary organic gases and particles on a global scale, partly from domestic combustion. While there is growing understanding of the composition and characteristics of these emissions, uncertainties still exist in chemical compositions with respect to different fuel types and burning conditions. However, developments in online instrumentation have allowed for not just the detailed chemical characterisation, but also the temporal resolution necessary to separate emissions according to the combustion conditions. Controlled experiments were carried out in the Manchester Aerosol Chamber to chemically characterise the composition of primary or fresh emissions from a domestic stove, using different biomass fuels, by performing controlled dilutor injections into the chamber, employing a combination of online and offline measurements, and comparing results according to different combustion phases (flaming vs smouldering). A chemical ionization mass spectrometer coupled with a Filter Inlet for Gases and Aerosols inlet (FIGAERO-CIMS) was utilized to investigate the variations in the oxygenated (CHO) and nitrogen-containing (CHON) organic gas and particle-phase compositions, while the aerosol mass spectrometer (AMS) was employed to provide information on the primary aerosol bulk chemical composition. The CHO compounds were more abundant, contributing a higher signal fraction in wood emissions compared to leaves and peat, and with wood smouldering yielding higher CHO fraction than flaming. The CHON compounds, though of significantly lesser contributions (<20%), were dominated by reduced nitrogen and organonitrogen compounds in the gas and particle phase respectively. The CHON compounds displayed greater aromaticity than the CHO compounds due to their higher double bond equivalent to carbon number (DBE/C) and aromaticity index (AI) values. Greater fraction of CHON compounds resulted in greater aromaticity in wood flaming compared to the smouldering emissions in the particle phase. Leaves exhibited higher aromaticity than wood and peat due to the presence of CHON compounds with greater DBE/C and AI values. Although, the results showed differences in primary aerosol composition by biomass type, the effect of burning conditions in the aerosol particles was only noticeable by the variations in the AMS f_{60} , suggesting that the f_{60} is a useful metric to differentiate emissions from flaming and smouldering burning phases.

Keywords: Biomass Burning, Peat, Leaves, Conventional fuels, Organic Aerosols, Primary Emissions, Manchester Aerosol Chamber, Chemical Characterisation, Domestic Stove.



1. Introduction

Biomass burning (BB) is a significant source of atmospheric aerosols, contributing two-thirds of the primary organic aerosol (POA) emitted globally, one-third of the global BC budget and the second-largest source of atmospheric VOCs, after biogenic emissions.^{1,2} BB emissions, can upon further reactions in the atmosphere, produce secondary organic aerosols (SOAs).³ The emissions from the burning of biomass can be influenced by the combustion conditions involving either flaming or smouldering phases, with the smouldering-phase BB producing higher POA emissions than the flaming.⁴ While studies have shown that biomass burning emissions are detrimental to human health, air quality and climate,⁵ a lot of uncertainty still exists in the understanding of the composition and characteristics of these emissions, which hinders the appreciation and description of consequent SOA formation in the atmosphere.⁶

Within areas such as the UK, there has been a proliferation and utilisation of improved small-scale biomass burners such as woodburning stoves as a low-cost option to meeting residential heating demands. Data provided by UK National Atmospheric Emissions Inventory (NAEI) indicates that in 2020, residential burning was responsible for 19.8 kt of PM_{2.5} emissions, with wood combustion accounting for 17% of that. In addition, the NAEI also estimated a 50% increase every two to three years in the increase in domestic stove installations from 2003 onwards.⁷ This greatly increases the need to thoroughly characterise the emissions from domestic appliances in order to ascertain their human health and climatic effects.⁶

Previous studies have explored the chemical characteristics of biomass fuels.^{6,8,9} Several of these studies focused largely on wood and other fuel types, but peat and leaves were outside its scope. In certain parts of the UK for instance, peat happens to be an important biomass fuel for domestic energy supply^{10,11} and its potential as a significant global emission source has been identified.¹² To our knowledge, very few studies have investigated peat and leaves combustion in a woodburning stove, despite the prevalent use of woodstoves to burn peat in certain European countries,¹¹ and the capabilities of wood burners as a useful tool for understanding emissions from different fuel types. Moreso, while a significant number of studies have attempted to investigate primary emissions from the burning of different fuels using the AMS, proton transfer-reaction time-of-flight mass spectrometry (PTR-ToF-MS) among others,^{8,13,14} not many have utilized the FIGAERO-CIMS in laboratory-controlled burning despite its recent notoriety in atmospheric researches and recognized high time resolution, selectivity and sensitivity to a wide range of oxygenated and nitrogenated VOCs.¹⁵⁻¹⁷

While many characterisation studies have focused on individual molecules, complex sources such as wood combustion can deliver a highly complex mixture, which is difficult to interpret. Therefore, to aid interpretation, it is often best to generalise molecular data according to metrics related to carbon number and/or functionality. According to Kroll *et al.*¹⁸ the degree of oxidation (O:C ratio), and the carbon oxidation state (OSc), are a critical metrics of characterizing the chemistry of organic aerosols because of their influence on toxicity, hygroscopicity and optical property.¹⁹ Moreover, studies have also shown that BB emit significant quantities of nitrogen-containing organic aerosols (NOAs), including nitrates, N-heterocyclic compounds, nitroaromatic compounds, and amines into the



atmosphere.²⁰ Nitrogen-containing organic compounds such as some N-heterocyclic compounds and nitroaromatics contribute to cloud water, light-absorbing organic compounds, also termed brown carbon (BrC),²¹ as well as SOAs;²² hence these compounds significantly affect climate changes and the Earth's radiation balance. Nitroaromatics are especially known for their adverse human health effects, because of their phytotoxic, carcinogenic and mutagenic properties.²³

Therefore, this study aims to highlight the differences in composition and chemical properties between conventional fuels (hard and soft wood) versus peat and leaves, which will enhance source prediction and the understanding of secondary formation in the atmosphere from these fuels, as well as their potential air quality, health and climatic effects. Specific objectives of the study entail to: 1) identify the differences in primary aerosol composition with respect to fuel type and burning conditions; 2) determine the dependencies of the composition and chemical properties in the gas and particle-phase on fuel type and burning phase. The study utilises a CIMS to characterise the oxygenated and nitrogen-containing fraction of primary emissions from the combustion of biomass fuels in a woodburning stove. Additional online measurement techniques were employed to further enhance the understanding of the BBA bulk chemical properties.

2. Experimental Methods

2.1. Description of Experimental Design

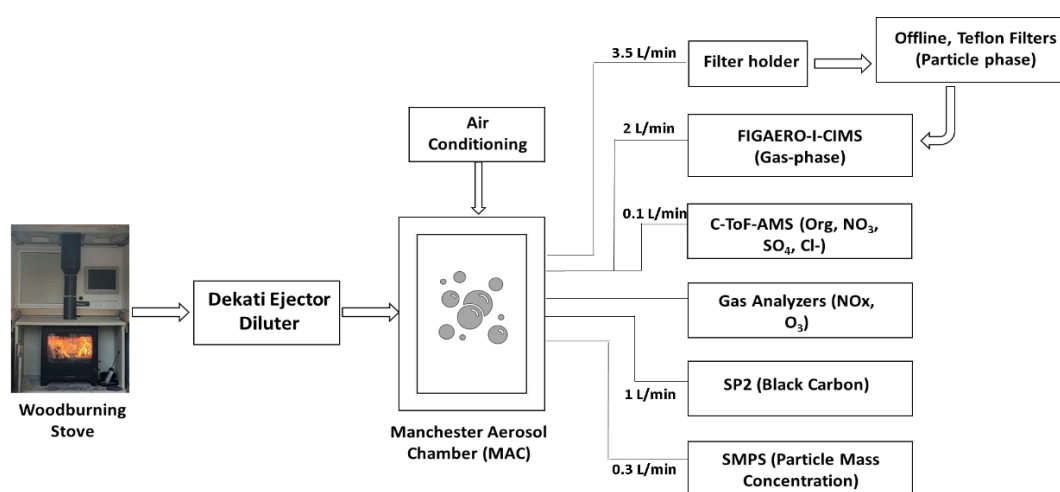


Fig. 1: The schematic of the experimental setup for the biomass burning chamber experiments. C-ToF-AMS: Compact Time of Flight Aerosol Mass Spectrometer; SP2: Single Particle Soot Photometer

Laboratory stove experiments were conducted as part of a characterisation study in preparation for the NERC HIP-TOX project,²⁴ designed to commission and chemically characterise a stove facility and chamber injection protocol for subsequent use in *in vivo* human exposure studies, the results of which will be presented in future publications. These experiments (Table 1) were carried out at the Manchester Aerosol Chamber (MAC) laboratory of the University of Manchester, UK.^{6,25,26} A schematic of the experimental setup is illustrated in Fig. 1. The chamber offers the possibility of “holding” the primary emissions, for detailed characterization with a large array of instruments, in a manner similar to Liu *et al.*²⁷ The biomass smoke from the flue was diluted with compressed dry air at a flow rate of 2 L/min,



in order to avoid re-condensation of evaporated materials and coagulation in the ½ inch stainless steel pipe that was used to channel the smoke from the smokestack to the chamber.²⁸ This was done continuously for the duration of smoke injection into the chamber. Smoke injection into the MAC was performed by an ejector diluter (eDiluter Pro, Dekati Ltd.). The eDiluter was used to control the injection of emissions into the chamber, until $190.36 \pm 51.18 \mu\text{g}/\text{m}^3$ (measured using a Scanning Mobility Particle Sizer, SMPS) particle mass concentration was attained.

A description of MAC has been presented by Shao *et al.*²⁹ In brief, the MAC is an 18 m³ fluorinated ethylene propylene (FEP) teflon bag suspended from a frame comprising a central fixed-frame member and two moving members, all contained within a temperature and relative humidity (RH) controlled enclosure. Filtered air, via a series of fill/flush cycles, is injected into the chamber by passing laboratory air at a flowrate of 3 m³/min through a combination of Purafil, charcoal, and HEPA filters arranged in series. Chamber conditions during the experiment were controlled at $25 \pm 1^\circ\text{C}$ and 50-60% RH. The temperature was controlled by the chamber air conditioning system and the humidity levels were controlled by the air dryer, which allowed the introduction of dry or humid air.

Biomass burning smoke was injected into the MAC through an Ecodesign wood stove (Esse Model 175F; fitted in a trailer adjacent to the MAC. The major characteristics of this stove in comparison to the conventional stoves in the UK market, is its promise of “precision burning” through its “particulate reburn” technology (serving the same purpose as the “tertiary air” systems), potentially improving its ability to reduce the particulate emissions below the threshold for Ecodesign compliance set out by the EU Commission Regulation.³⁰ However, the “clean” or “precision burning” capacity of the wood stove was disabled through the removal of the catalytic filter, to simulate more conventional domestic stove emissions. The Biomass types selected for this study were beech wood (hardwood representative of domestic fuels in current use in the UK), softwood (ponderosa pine), peat and leaves (Hornbeam or *Carpinus betulus*). The fuels selected represented components present in domestic burning (wood and peat) as well as wildfires (wood, peat and leaves). Moreover, peat, although not a widely recognized fuel used for domestic burning, is one of the widely used sources of fuels for residential heating purposes in the Republic of Ireland, Finland, and parts of Northern Ireland.^{10,11} This study may also be relevant for the understanding of wildfire emissions,³¹ although it should be noted that the combustion conditions in a domestic stove are likely to be very different. A summary of the initial experimental conditions is presented in Table 1, and the experiments are hereafter referred to by their four-letter labels. Moreover, Fig. S1 shows a CIMS gas-phase time-series of selected compounds in the HWFL experiment (Table 1). The time periods before smoke injection, the smoke injection time and periods after smoke injection are shown.

Table 1: Summary of Initial Experimental Conditions for the Stove Experiments

Experiment	Fuel Type	Burning Condition	Experiment Label	PM Concentration ($\mu\text{g}/\text{m}^3$)	OA ($\mu\text{g}/\text{m}^3$)	OA/BC	NO ₃ ⁻ ($\mu\text{g}/\text{m}^3$)	NO _x (ppb)
1.	Hardwood (Beech)	Flaming	HWFL	256.34	15.88	0.33	2.27	91.84

2.	Hardwood (Beech)	Smouldering	HWSM	139.03	41.05	4.31	2.97	86.43
3.	Softwood (Pine)	Flaming	SWFL	149.53	4.66	0.12	0.49	58.20
4.	Softwood (Pine)	Smouldering	SWSM	111.09	30.31	4.4	1.75	90.69
5.	Softwood (Pine)	Smouldering	SWSM	215.86	66.11	-	3.13	69.56
6.	Leaves (Hornbeam)	Smouldering- like	Leaves	226.03	84.96	-	2.57	38.19
7.	Leaves (Hornbeam)	Smouldering- like	Leaves	222.95	-	-	-	36.66
8.	Leaves (Hornbeam)	Smouldering- like	Leaves	179.50	60.28	-	2.21	29.52
9.	Peat	Smouldering- like	Peat	138.76	64.36	-	0.51	25.09
10.	Peat	Smouldering- like	Peat	264.50	112.59	-	0.80	25.23
11.	Chamber Background Experiment			0.10	-	0.10	0	21.73
12.	Chamber Background Experiment			0.19	-	0.19	0	21.81

* OA = AMS organics; NO₃⁻ refers to AMS nitrate

The wood fuels were burnt under “flaming” and “smouldering” combustion phases. Similar to the study by Bertrand *et al.*⁸ and the protocol used in Allan *et al.*,³² fire starters and wood kindling were used to ignite the fire. The door of the wood stove was initially kept ajar to aid ignition. The woodstove was then shut after ignition and left until the kindling and starters were completely burnt, before injection of emissions into the chamber commenced. The smoke from the ignition phase was deliberately excluded during smoke injection because it was not indicative of the overall burning of the biomass fuels in the woodstove, due to the presence of the fire starters and kindling.

Furthermore, the burn phases were controlled by varying the air/fuel ratio through the opening and closing of the stove’s air restriction valve during burning, to attain flaming or “smouldering” conditions respectively. For the burning phase designated “smouldering” here, fresh wood was added in a manner consistent with the refuelling procedure in the conventional operation of the woodstove in homes, and the smoke injection in the smouldering phase was carried out when there were no more visible flames. It should be noted that the description of ‘smouldering’ used here is for the sake of consistency with other publications from this experiment,^{4,25} but it should be noted that the emissions will consist of a combination of emissions from weak combustion of embers from the previous load, and un-combusted pyrolysis emissions from the fresh wood. These pyrolysis emissions have been characterised in previous studies and are known to be chemically and physically distinct from combustion emissions.³³

2.2. Instrumentation

Online and offline CIMS measurements of the gas and particle phases respectively, were carried out by a FIGAERO-CIMS.^{34,35} The instrument was operated with Iodide (I-) reagent ion in all the experiments,



produced by passing a mix of CH₃I and ultra-high purity nitrogen over a polonium (²¹⁰Po) radioactive source. This reagent system is useful for the general study of functionalised organic molecules with moderate to high polarity, but it should be noted that it is incapable of detecting non-polar molecules, so pure hydrocarbons are not included in this study. The FIGAERO-CIMS which combines the High-Resolution Time-of-Flight CIMS (HR-ToF-CIMS) coupled with the Filter Inlet for Gases and Aerosols (FIGAERO), was first introduced by Lopez-Hilfiker *et al.*³⁵ The offline FIGAERO-CIMS filter analysis followed this procedure: The filters were desorbed using dry ultra-high purity nitrogen (UHP N₂). The desorption cycle was programmed thus: 2 mins of background measurement (Zero), 25 mins temperature ramp (from ambient to 200°C), 15 mins temperature soak (where the temperature was kept constant at 200°C to ensure complete filter desorption); 20 mins temperature cool and 2 mins of Zero.

PTFE filter samples (MitexTM PTFE, pore size 5.0 µm, diam. 47mm) were collected with a polycarbonate 47-mm in-line filter holder, at a flow rate of 3.5 L/m. The teflon filters were prebaked at 200°C for 24 hours prior to sample collection. After collection, they were placed in a petri dish (AnalyslideTM, Pall Laboratory, 47mm diam., Base and Lid: Polystyrene), placed inside a tightly locked ziplock bag, and stored frozen until thermal desorption with the FIGAERO-CIMS. Offline filters were sampled during these experiments because the thermocouples of the FIGAERO, responsible for temperature controls during the filter desorption phase, developed a fault just before the commencement of the experimental campaign, and couldn't be replaced in time for the start of the experiments.

The compact time-of-flight aerosol mass spectrometer (C-ToF-AMS) and the SP2 were respectively utilized to explore the composition of the non-refractory (organics, sulfate, nitrate, ammonium, chloride as well as key marker ions) and refractory (black carbon) components in the aerosol particle phase BB emissions, as was previously done.³³ The AMS was calibrated using the standard protocol with ammonium nitrate and the SP2 with Aquadag, using the standard calibration factor of 0.75.³⁶ The AMS f_{43} , f_{44} and f_{60} were determined by taking the ratio of these marker peaks divided by the total organic signal.³⁷ The AMS O:C ratio was also computed as determined by Aiken *et al.*,³⁸ which is based on the empirical fit between f_{44} and the AMS O:C ratio. NO_x measurements were carried out using a chemiluminescent analyzer with a molybdenum converter (Thermo Scientific, model 42i).

2.2.1. Data processing and analysis

High-resolution peak fitting of the CIMS data mass spectra was carried out with Igor 7 (WaveMetrics, USA) and Tofware 3.2.3 (Tofwerk AG, Switzerland). Mass calibration of the spectra was carried out using I⁻, I₂⁻, CH₂O₂I⁻ and I₃⁻ ions. The identified peaks considered ranged from m/z 180–500 (excluding the reagent ions, I₂⁻, and I₃⁻). Identification and assignment of peaks in the mass spectra was primarily assisted by clear identification of compounds confirmed in previous BB studies,^{6,17,39} and majority of the peaks identified in this study fell under this category. Secondly for peaks that couldn't been determined from previous studies, assignment of a chemically valid formula as determined from pubchem (<https://pubchem.ncbi.nlm.nih.gov/>) was completed keeping the mass error under ±10 ppm. The unassigned fractions in the CIMS measurements (less than 20% of total fitted signal) represent the peaks that are difficult to identify, caused by either poor signal-to-noise ratios ($S/N \geq 2$) or inaccessible formulae within the trusted error. The signals reported in this study are integrated signals in counts per



second (cps), normalized by the sum of the iodide (I^-) and water-iodide adduct (H_2OI^-) signals. Normalizing individual compound signals to the sum of reagent ions ($I^- + H_2OI^-$) is widely used in CIMS studies,^{15,35} and was done to reduce the effects of variations in the reagent ion concentrations and overall instrument sensitivity. The CIMS measurements in both phases were subjected to a two-step subtraction process in order to account for the chamber and filter background and any potential instrument contamination. The method of background subtraction is described in the supplementary information (Fig. S2).

Though previous attempts have been made to constrain the limitations associated with the quantification from FIGAERO-CIMS in both the particle and gas phases,¹⁶ challenges persist due to experimental limitations and a lack of available standards.⁴⁰ It should be noted that recent advancements in instrumentation (e.g. voltage scanning) has made progress to constrain sensitivities. While standards are available for some compounds detected in this study and these can be calibrated for individually, it is currently implausible to perform calibrations for all compounds identified in CIMS mass spectra with each compound possibly containing multiple isomers that may have different response factors in the CIMS instrument. Hence, we assume uniform sensitivities across the whole range of detected compounds and used normalized signals for the comparisons presented in this study, like previous studies.^{6,41,42} Chen *et al.*,⁴² noted that this assumption was reasonable as they found a good correlation between the total OA measured by the FIGAERO-CIMS and the AMS. However, it should be noted that the uncertainty arising from the assumption of uniform sensitivity may result in an overestimation of the importance of more oxygenated compounds, compared to the less oxygenated, due to their relative affinity to the reagent ions.¹⁵

Similar to the study of Kong *et al.*,⁶ who performed an ordinal analysis to determine the most significant masses through ranking before identifying the molecular composition of those masses, this study has applied a ranking system of the normalized signal contribution of the already identified masses in order to ascertain the most influential compounds emitted from each fuel type and burning condition. The top 30 most significant CHO and CHON compounds by normalized signal contribution have been discussed as fingerprint molecules of the emissions. It should be noted that this study has been limited to organic molecules with two or more carbons so HCN, HCNO, and HCOOH (formic acid), despite being among the top 30 compounds identified in the gas phase, are not discussed in this study. These compounds are also well reported in BB literature.^{17,43} We limited our CIMS analysis to two or more carbons to target higher molecular weight organic compounds which generally make a larger SOA contribution.

2.3. Elemental composition of identified molecules

The identified peaks from the analysis of the CIMS mass spectra were categorized based on their elemental composition. Compounds containing carbon, hydrogen and oxygen only were classed as oxygen-containing compounds or CHO subgroup while those containing only carbon, hydrogen, oxygen and nitrogen were categorized as CHON subgroup also referred to as nitrogen-containing organic compounds (NOCs). Moreover, the identified compounds were also subdivided according to the numbers of carbon atoms in their molecular formulae: C_2 – C_5 representing compounds with two to



five carbon atoms, C₆–C₈ representing compounds with six to eight carbon atoms, C₉–C₁₁ representing compounds with nine to eleven carbon atoms, C₁₂–C₁₆ representing compounds with twelve to sixteen carbon atoms, >C₁₆ representing compounds with sixteen carbon atoms greater than sixteen and “Others” representing CHO and CHON compounds with one carbon atom as well as compounds that are not in the CHO and CHON classes.

2.4. Computation of average carbon oxidation state (OSc), double bond equivalent (DBE) and aromaticity index (AI)

Studies have utilized the carbon oxidation state to characterize the chemical composition of organic molecules.^{39,44} Kroll *et al.*¹⁸ established the use of the OSc metric in the evaluation of the degree of oxidation within a complex oxidation reaction. OSc was computed as described by Du *et al.*⁴⁴ using the O:C, H:C, and N:C ratios as shown in equation 1;

$$\text{OSc} \approx 2 \times \text{O:C} - \text{H:C} - (\text{OSn} \times \text{N:C}) \quad (1)$$

where OSn = 0 if number of N atoms = 0. OSn = +3 if nO < 3 and +5 if nO ≥ 3.

Researchers have also previously characterized the chemical composition of organic aerosols by analysing the degree of unsaturation or the density of C–C double bonds in a molecule, in order to ascertain the existence of aromatic and condensed aromatic moieties in the molecule. This is useful to aid the understanding of potential toxicity effects.²⁹ In this study, aromaticity was estimated utilizing the double bond equivalent (DBE), and the ratio of double bond equivalent to carbon number (DBE/C). DBE/C is related to the density of double bonds and their aromaticity, with increasing values representing increasing contributions from compounds containing aromatic rings.^{45,46} The DBE value was computed as shown in equation 2;

$$\text{DBE} = \frac{2C+2-H+N}{2} \quad (2)$$

where C, H and N represent the number of carbon, hydrogen and nitrogen atoms respectively. Note that, DBE is independent of the number of oxygen atoms.

Furthermore, the possibility of double bonds being present in compounds, yet not contributing to aromaticity, condensation or ring formation; and so, makes the DBE/C ratio insufficient to explore the presence of aromatic compounds. They introduced the aromaticity index (AI) which is computed by the equation 3;

$$\text{AI} = \frac{1 + C - O - 0.5H}{C - O - N} \quad (3)$$

3. Results

3.1. Primary aerosol composition and influence of biomass type and burning conditions

The AMS data is presented first, as this provides context for the CIMS results when comparing to the extensive previous literature of stove and biomass burning emissions using this instrument. Table S1 shows the mass concentration of organics (OA), nitrate (NO₃⁻), ammonium (NH₄⁺), sulfate (SO₄²⁻), chloride (Cl⁻), black carbon (BC), mean organic aerosol to black carbon (OA/BC) ratio, AMS O:C ratio,



277 f_{43} , f_{44} and f_{60} for the different fuels and burning conditions. A plot of f_{44} and O:C (on the left and right
 278 axis respectively) against f_{60} is presented in Fig. 2 to further elucidate the aerosol chemical properties.
 279 The f_{44} corresponds in behaviour to O:C,³⁸ and increasing values indicate increasing degree of
 280 oxygenation and the presence of carboxylic acids.^{8,9} On the other hand, the f_{43} represents lesser
 281 oxygenation, while the f_{60} often indicates a signature for biomass burning, representing levoglucosan
 282 and similar molecules.^{13,38} Hence, the UMR ions m/z 43 ($C_2H_3O^+$ and $C_3H_7^+$), m/z 44 (CO_2^+) and
 283 m/z 60 ($C_2H_4O_2^+$), serve as tracer fragments for total OA, OOA and BBOA respectively.¹³

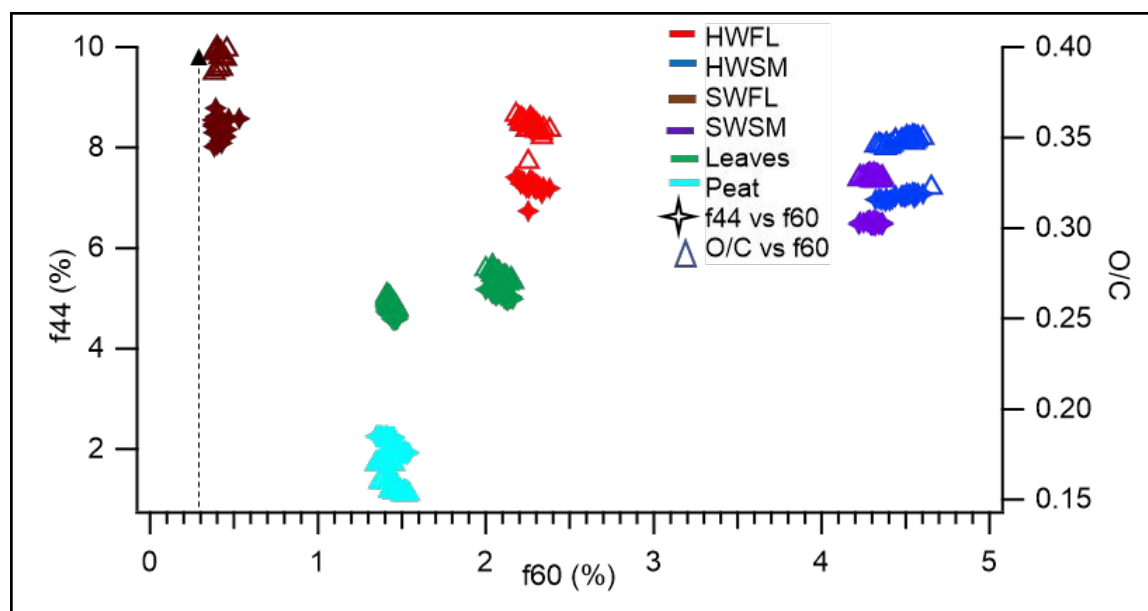


Fig. 2: f_{44} (left-axis) and O:C (right-axis) vs. f_{60} (bottom-axis). The vertical dashed line represents the Cubison *et al.*³⁷ f_{60} background level

Fig. 2 indicates variability in the trends among the different biomass types and burning conditions and the observed values were within range of the results of primary BBOA in ambient environments.^{37,47} On average, peat emitted the highest fraction of organics, followed by leaves and then wood. Wood fuel types had the largest BC values, with negligible values observed in leaves and peat aerosol. OA and AMS total particulate nitrate were higher in wood smouldering compared to flaming, while BC was higher in flaming compared to smouldering (Fig. S3). Also, nitrate in leaves were comparable to wood, while the lowest concentrations were observed in peat particles. Fig. S3 shows similarities in the aerosol chemical compositions of repeat experiments for leaves and peat, indicating good repeatable and reproducible chemical characteristics of the organic aerosol in these experiments. Fig. S4 showing repeat experiments for selected CIMS gas-phase markers also demonstrates good repeatability. The highest f_{44} and O:C values were observed in the wood aerosols. The f_{43} values were highest in peat and lowest in wood aerosols.

Stove emissions measured here show distinct chemical signatures based on fuel type and burn conditions, with variations in oxygenation (f_{44} , O:C) and biomass burning tracers (f_{60}) influencing their atmospheric behaviour. These differences are critical for improving source apportionment and understanding the health and climate impacts of primary organic aerosols.



3.2. FIGAERO-CIMS analysis of gas and particle-phase compounds

3.2.1. Elemental composition of gas and particle-phase compounds

View Article Online
DOI: 10.1039/D5EA00080G

The contributions of different functionalities such as the CHO and CHON groups, and the carbon number groups are presented in Fig. 3 for all the compounds identified in this study, and these reveal differences in elemental composition due to fuel type and burning condition based on the normalized fractional signals.

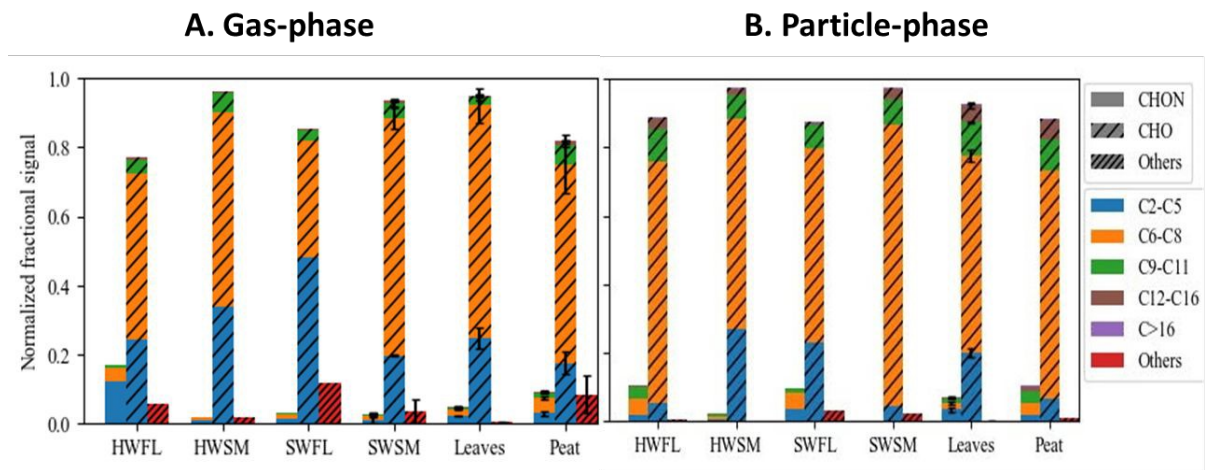


Fig. 3: Elemental Composition of BB (a). Gas-phase and (b). Particle-phase organics across all experiments. “Others” include non-CHO and non-CHON compounds identified such as nitric acid (HNO₃) as well as C1 compounds. (4a). Standard deviations for (A) SWSM (n = 2), Leaves (n = 3) and for Peat (n = 2); (B) Leaves (n = 2), are represented by error bars.

CHO compounds

The oxygenated organic aerosols (OOA or CHO) dominated the primary gas and particle phase BB emissions (Fig. 3) across all fuel types and burning conditions. The CHO fraction, on average, was higher in wood followed by leaves and then peat, in both gas and particle phase. On average, softwood emitted more CHO compounds than hardwood in both gas and particle phases. Smouldering emissions were observed to have a higher fraction of the oxygenated organic compounds compared to the flaming burns in this study. The C₆–C₈ fraction was observed to have the most fractional contribution to the emissions in both gas and particle phase. This fraction was dominated by C₆H₆O₂, C₇H₈O₂, C₈H₁₀O₂ and C₆H₆O₃ in the gas phase, and the widely established biomass burning tracer C₆H₁₀O₅, in the particle phase. Higher dominance of the oxygenated C₆–C₈ group was observed in wood smouldering compared to the flaming-phase. The low molecular weight C₂–C₅ compounds were the next most significant faction and were dominated largely by C₂H₄O₂, C₃H₆O₃, C₅H₈O₃, and C₅H₈O₄ in the gas-phase and C₂H₄O₃, C₄H₆O₄, C₅H₆O₄, C₅H₈O₄ in the particle phase. The signal fraction contributed by compounds with >C₉ were comparably higher in the particle phase compared to the gas phase.

CHON compounds

The nitrogen-containing compounds (CHON or NOCs) contributed <20% of the combined signals for all the identified compounds in both the gas and particle phase, across all fuel types and burning conditions. Contributions of gaseous CHON was highest in hardwood flaming. In the particle phase, the CHON fraction was comparable in wood flaming, leaves and peat emissions. Flaming emissions

generally displayed a greater abundance of CHON compounds than smouldering for both wood types. The NOCs were observed to be dominated by the low molecular weight C_2 – C_5 compounds. Major contributors in this class of compounds in the gas phase were C_2H_3NO , $C_2H_5NO_3$, $C_3H_3NO_2$, and $C_3H_5NO_2$; $C_5H_7NO_3$, $C_5H_9NO_3$, $C_3H_5NO_3$ and $C_3H_3NO_2$, were among the top compounds in the particle phase. There was a noticeable, but low contribution from the C_6 – C_8 and C_9 – C_{11} classes in the gas and particle phase.

3.2.2. Chemical characterization of gas and particle-phase compounds

To evaluate the differences in chemical properties of gas and particle-phase primary emissions from the different fuel types and burning conditions, we present the results from the elemental ratios of H:C and O:C, the OSc, and the aromaticity indices such as DBE, DBE/C and AI for the top 30 gas and particle-phase compounds.

Elemental ratios of the major gas and particle-phase compounds

The O:C of the 30 most significant oxygenated and nitrogen-containing compounds had very similar ranges in the gas-phase and more variability in the particle phase, across different fuel types. Fig. S6 shows that most of the top 30 gas and particle-phase OOA and NOA compounds occur within the region of $O:C < 1$ and $1 < H:C < 2$. On average, the gas and particle phase O:C of the oxygenated compounds was in the range of 0.55 - 0.65 and 0.54 - 0.65 respectively. The nitrogen-containing compounds had relatively lower O:C on average, ranging from 0.40 - 0.71 and 0.43 - 0.55 in the gas and particle phase respectively. The mean H:C of the oxygenated compounds was in the range of 1.40 - 1.43 and 1.39 - 1.53 in the gas and particle phase respectively. The nitrogen-containing compounds had ranges from 1.35 - 1.57 and 1.26 - 1.49 in the gas and particle phase respectively.

Furthermore, most of the top 30 N-containing organic compounds across all experiments in the gas phase exhibited O:N values of < 3 except in the hard and soft wood smouldering, which had a significant number $O:N \geq 3$ (Fig. S7A). More experiments in the particle phase, demonstrated $O:N \geq 3$ (Fig. S7B).

OSc vs. nC of the major gas and particle-phase compounds

Fig. S8A and B shows that the OSc have comparable ranges across all experiments, with the top 30 CHO and CHON compounds in the gas and particle phase distributed with the region of $-2 \leq OSc \leq 1$. It should be noted that OSc for the CHON compounds factors in the oxidation state of nitrogen (OSn), as captured in Equation 1. On average, the OSc of the combined top 30 CHO and CHON species among all burns ranged from -0.76 to -1, with leaves and peat demonstrating higher mean values than the woodburning emissions. Moreover, the clear separation between the CHO and CHON gas-phase compounds observed in all burns irrespective of fuel type or combustion condition, aligns with the observations in the O:C values, and corroborates the assertions that oxygenated organic compounds are expected to have a degree of oxidation than the nitrogen-containing organic compounds.



Open Access Article. Published on 01 October 2025. Downloaded on 10/4/2025 11:00:05 PM.
This article is licensed under a Creative Commons Attribution 3.0 Unported Licence.



Aromaticity estimation of the major particle-phase compounds

To further investigate differences in the chemistry of the emissions from the different fuels and burn phase, the aromaticity of the top 30 most significant compounds in the particle phase were quantified using the DBE, DBE/C ratio and AI, and presented in Fig. 4.

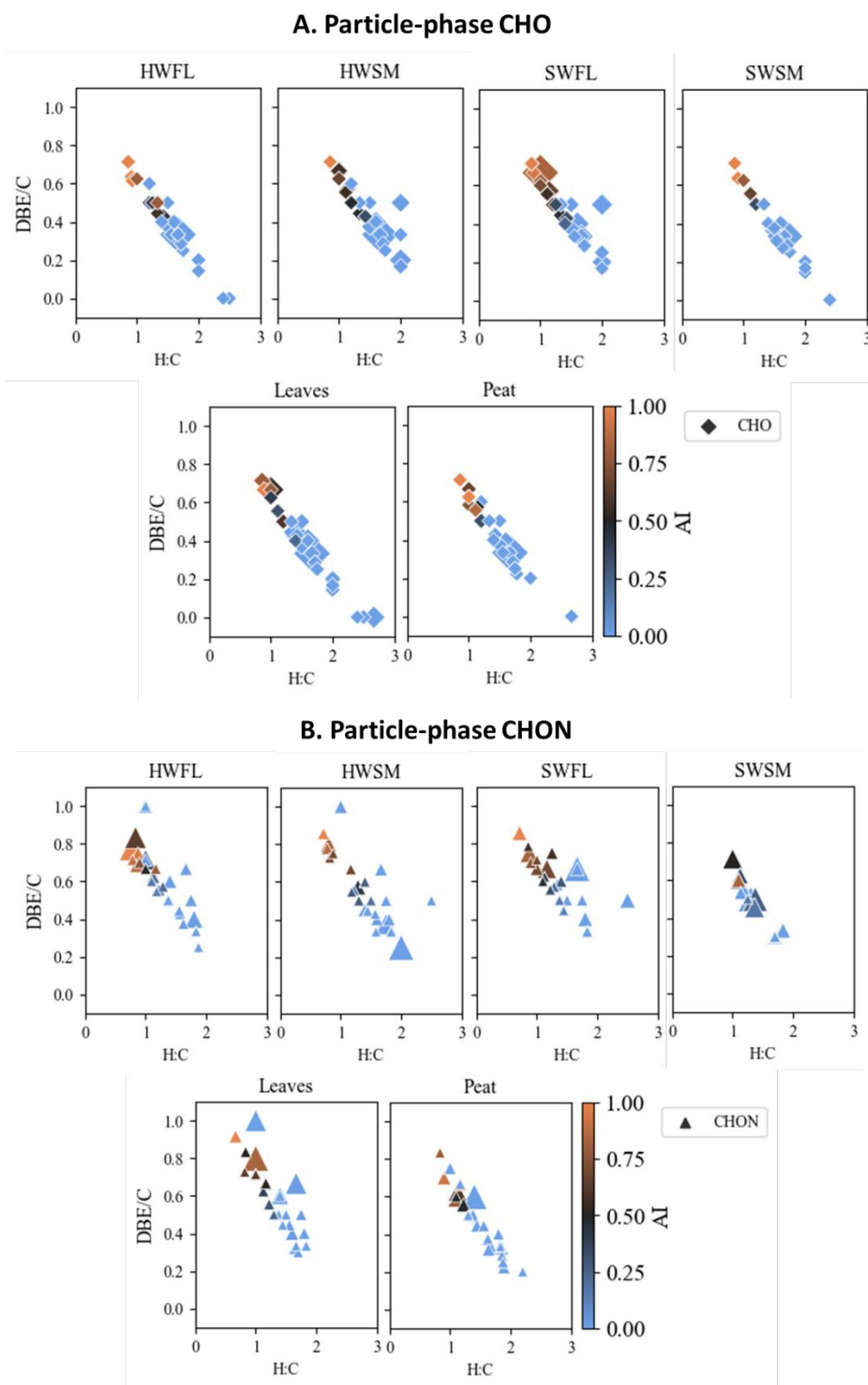


Fig. 4: Particle phase DBE/C vs. H:C ratios in (A) CHO compounds. (B) CHON compounds for different fuel types coloured-scaled with the aromaticity index

DBE/C and AI values associated with CHON were higher than those associated with the CHO compounds across all biomass types (Fig. 4A and B). Studies show that a threshold $\text{DBE/C} \geq 0.67$

indicate minimum criterion for the presence of molecules containing condensed aromatic rings; compounds with $AI > 0.5$ is classified as aromatic, and those with $AI \geq 0.67$ are classed as condensed aromatic compounds.⁴⁶ According to Koch and Dittmar,⁴⁶ generally, $AI > 0.5$ is the minimum criterion for the presence of aromatic species. This therefore means that the top 30 CHO and CHON compounds in the particle phase with maximum DBE/C of 0.71 and 1.0 respectively and AI values of 0.5 and 1.0 respectively, may contain aromatic and condensed aromatic molecules. In noteworthy that, although AI is a more conservative approach to aromaticity estimation, it provides more reliable information than the DBE/C metric.⁴⁶

Fig. 4A and B provides information on the aromaticity of the top 30 CHO and CHON compounds in the particle-phase of the different fuel types. As expected, similar behaviour was observed among the CHO compounds in all the fuel types since DBE is independent of oxygen number (Fig. 4A).⁴⁶ The DBE/C ratio displayed an inverse relationship versus H:C consistent with the observations of Koch and Dittmar,⁴⁶ that an increasing number of H atoms in a molecule decreases unsaturation (lower DBE values) and vice-versa. Fig. 4B (CHON) also shows that aromatic compounds were more prevalent as more nitrogen-containing compounds than oxygenated compounds appear above the aromaticity threshold of $DBE/C \geq 0.67$ and $AI > 0.5$. This suggests that the CHON compounds may contribute more to aromaticity in organic aerosols than CHO compounds, and may also contain larger chromophoric substances.⁴⁵ Fig. 4B also reveals a higher number of compounds (and with larger signal intensity) in the aromatic region for hardwood flaming phase emissions compared to their smouldering phases. Similar observation was noted for softwood flaming in comparison to smouldering. In addition, it was also observed that leaves may emit more aromatic compounds in comparison to other fuel types, containing compounds with the highest AI and DBE/C values of 1 in the particle phase.

4.0 Discussion

4.1. Insights from primary aerosol composition according to AMS data

4.1.1 Differences in aerosol composition by fuel type

When looking at the AMS data, our results indicate differences in the aerosol composition based on the different fuel types used here. Differences in emissions are likely because of the difference in composition.^{13,48} However, the observed higher levels of organic aerosol in peat compared to wood in this study is not consistent with a previous report involving quadrupole-ACSM measurement directly from a stove,¹¹ probably due to the design and operation of the stove used in their study. The low BC values observed for peat and leaves in this study, compared to wood, are consistent with the findings of Engling *et al.*⁴⁹ who explained that the combustion process for peat is akin to a smouldering combustion (characterized by low combustion efficiency), hence peat emissions contain high organic contents but low BC. This is also applicable to leaves burning. In addition, the OA/BC ratios of this study fall within the range observed by McClure *et al.*⁹ who reported OA/BC ratios varying between 0.3 – 10 from the laboratory combustion and study of different biomass fuels including softwood, hardwood and peat in their chamber.



The f_{44} (and O:C by extension), as well as f_{60} values were higher in wood-burning aerosols compared to leaves and peat, excluding the softwood flaming burn which had the lowest f_{60} (Fig. 2). This indicates that the primary wood aerosols displayed greater degree of oxygenation compared to leaves and peat, with leaves combustion exhibiting a higher oxygenation to peat. While previous studies have compared the differences in oxygenation in wood and peat aerosols,¹¹ there is little or no information on that of leaves. Chen *et al.*⁵⁰ observed similarly low f_{44} values for peat in their study using a combustion chamber and suggested that primary aerosols from peat are not highly oxygenated. Similar to this study, lower f_{60} values for peat in comparison with wood have previously been found.¹¹ This may be because of the lower cellulosic content of peat.⁵¹ f_{60} is a marker for levoglucosan, a product of the pyrolysis of cellulose and hemicellulose, hence lower levoglucosan levels in peat compared to wood will result in lower f_{60} values from peat combustion. However, the higher f_{43} values in peat compared to wood and leaves aerosol particles observed in this study, is consistent with the results of Lin *et al.*,¹¹ who noted higher levels of m/z 43 in peat than in wood.

4.1.2. Differences in wood aerosol composition by burning condition

The wood smouldering combustion produced a higher organic aerosol concentration hence higher OA/BC, while the flaming burns produced the largest BC concentrations and lower higher OA/BC (Table S1), in agreement with a previous flaming and smouldering woodstove observations.²⁸ Similarly, higher total particulate nitrate levels were observed in wood smouldering compared to flaming. The higher OA/BC in smouldering compared to flaming aerosol particles suggests that the smouldering may result in a higher SOA yield compared to the flaming, previously observed using a wood stove.²⁸ The flaming burn had higher O:C and slightly higher f_{44} values than smouldering, both indicating more oxygenated OA. The f_{44} trend in this study is consistent with observations of Bertrand *et al.*⁸ in their wood burning study using a logwood stove and pellet burner. However, Weimer *et al.*⁵² using a wood stove and automatic burner to study different wood types, observed higher m/z44 values in smouldering phase compared to flaming. While hardwood aerosols had very similar f_{44} and O:C values irrespective of burning condition, softwood aerosols exhibited more differences between the burning phases (Fig. 2). The f_{43} values were comparable in both burning phases (Table S1) and may be limited as a metric to differentiate between burn phases. The inorganic species collectively exhibited a higher dominance in the smouldering phase compared to flaming aerosols.

As shown in Fig. 2, the smouldering conditions displayed higher f_{60} values than the flaming, in consonance with previous flaming and smouldering observations in a woodstove⁸ and simulated wildfires.⁵³ This suggest that f_{60} may be a useful metric to differentiate between flaming and smouldering burns, however McClure *et al.*⁹ differs, stating that f_{60} is not a useful metric to distinguish between different burn conditions because of their observation of very similar f_{60} values in both flaming and smouldering phase, albeit from a wildfire simulation study. Furthermore, Fig. 2 reveal that most of the aerosols are elevated well above the 0.3% of OA f_{60} background level as expected for BB-impacted air masses.³⁷ Interestingly, softwood flaming aerosols are positioned very close to f_{60} background line, demonstrating a behaviour akin to air masses with negligible BB influence.^{54,55} The low f_{60} values



observed in softwood flaming may be attributed to the relatively lower levels of $C_6H_{10}O_5$ (levoglucosan and levoglucosan-like molecules) in comparison to other experiments (Fig. S5B). Cubison *et al.*³⁷ opines that f_{60} is required stay above 0.3% of OA background line for effective BBOA source prediction analysis using PMF. This therefore implies that it may be difficult to detect an air-mass influenced by softwood flaming aerosols in the atmosphere. This finding supports the notion from previous studies that the use of levoglucosan as a marker of wood burning has high uncertainties.⁵⁶

4.2. Differences in FIGAERO-CIMS gas and particle phase composition and characteristics due to fuel type

The dominance of oxygenated compounds (OOA) irrespective of fuel type observed in this study is consistent with previous observations from a variety of biomass fuels using different appliances.^{57,58} Higher mean levels of OOA in softwood than hardwood is probably because softwoods have resin canals that facilitate the storage of volatile terpenes (monoterpenes and sesquiterpenes), unlike hardwoods.⁵⁹ OOAs are important because of their significant contribution to SOA formation in the atmosphere due to their high reactivity and wide range of volatility.^{39,60}

Among the CHO group, $C_6H_6O_2$, an aromatic, phenolic OOA shows dominance by signal fraction (a range of 8.7 – 39%) across all biomass types in the gas-phase consistently appearing in the top 3 most influential compounds by percentage contribution (Fig. S5A). $C_6H_6O_2$ observed in this study may be attributed to catechol since this isomer has been widely identified in BB studies.⁶¹ The greatest $C_6H_6O_2$ contribution was observed in leaves followed by peat with the lowest in softwood flaming. Although $C_6H_6O_2$ is well recognized as a component of POA from BB, to our knowledge, there is little or no information on its dominance in primary BB emissions. The dominance by signal of $C_6H_6O_2$ in the wood burning emissions, observed in this study, may be due to its formation from guaiacol radicals, produced from the breakdown of guaiacol at high temperatures.⁶ However, this does not offer explanation for the high levels of $C_6H_6O_2$ in leaves and peat which were combusted at much lower temperatures. The high levels of $C_6H_6O_2$ in leaves and peat in this study could be attributed to their high lignin content, since $C_6H_6O_2$ is a product of lignin pyrolysis.⁶² The observed abundance of $C_6H_6O_2$ in the solid fuels' emissions of this study (wood and peat) and its potential transformation to nitrocatechol ($C_6H_5NO_4$), suggests possible health implications for domestic solid-fuel burning due to its recognized toxicity, and climate impacts from its contribution to BrC aerosol formation.⁶³ In a previous laboratory BB study, nitrocatechol emissions had the highest mass irrespective of the wood type.⁶⁴ $C_6H_{10}O_5$ recognized as levoglucosan and its isomeric derivatives such as mannosan and galactosan have long been established as biomass burning markers.^{13,39} It's recognition as the most dominant organic compound in the particle-phase as observed in this study (Fig. S5B), is known.⁶¹ Moreover, its accelerated gas-particle partitioning establishes its relatively low levels in the gas-phase of this study and abundance in the particle.⁶⁵

The low emissions of nitrogen-containing compounds in all the different fuel types is dominated by low-molecular weight CHON compounds, and comparable to the study of Zhou *et al.*⁶⁰ The abundance of O:N<3 compounds in the gas-phase CHON (Fig. S7A) indicate the presence of reduced nitrogen-containing functional groups such as imides, isocyanates and amines,⁵³ previously observed in biomass



burning emissions.¹⁷ The particle phase displayed a greater number of compounds with $O:N \geq 3$ across all fuel types (Fig. S7B), possibly indicating considerable presence of compounds with nitro ($-NO_2$) and/or organic nitrates ($-ONO_2$) functional groups. In this study, particulate organic nitrogen (ON) fraction in the primary emissions were observed higher than gaseous ON fractions, similarly reported by Cai *et al.*⁶⁶ Moreover, the relatively high fraction of CHON compounds in peat in the gas and particle phase (in comparison with the other fuels) may be a result of the known high nitrogen content of peat fuels.⁶⁷ Low contributions from CHON compounds observed in the gas and particle phase BB emissions of this study does not necessarily make them less important because certain classes of these compounds such as the NACs exhibits intense radiative forcing effects as well as detrimental impacts on health even at negligible concentrations which emphasizes the need for continuous investigation of their atmospheric behaviour and sources.⁶³

4.3. Differences in composition and characteristics due to combustion conditions

The observed higher fraction of the oxygenated compounds in wood smouldering emissions compared to flaming is consistent with the results of Stefenelli *et al.*⁶⁸ in their domestic stove emission study under flaming and smouldering conditions. The higher fraction of oxygenated OA in the smouldering gas and particle phase emissions indicate that the smouldering burn may contribute to higher SOA formation, cloud nucleation and hygroscopicity potential due to the presence of more oxygenated species.⁶⁹ The observed CHO contribution in the gas phase in the flaming phase of this study is highly consistent with previous flaming-phase observations.^{14,60} However, Evtyugina *et al.*⁷⁰ in their study of different wood fuels using a domestic woodstove and fireplace similarly under flaming conditions, observed much lower CHO contribution in their study, probably because they did not consider emissions from lower molecular weight organic gases like acetic acid, which are known to be emitted in large quantities in biomass emissions.^{14,58}

The higher fraction of the oxygenated C_6 – C_8 group in wood smouldering compared to flaming suggests that smouldering emissions may emit higher levels of oxygenated aromatic compounds. $C_6H_6O_2$ levels, being one of the most dominant compounds by signal, in the gas-phase were generally observed higher in smouldering conditions (associated with lower temperatures) compared to flaming. This is consistent with observations in previous studies and may be because methoxyphenols such as guaiacol are heat-sensitive, hence its decomposition may increase with temperature.^{6,8}

The relatively higher fraction of CHON compounds in hardwood flaming gas-phase emissions may be attributed to the observed higher NO_x concentrations (Fig. S9). This is supported by the positive correlation between NO (and NO_x) and CHON ($O:N \geq 3$, organic nitrates) previously observed.⁷¹ However, this offers no explanation for the observed low CHON contributions to hardwood smouldering in the gas-phase, with similarly high NO_x . Particle-phase CHON fraction was observed to be higher in both hard and soft wood flaming emissions compared to smouldering. In contrast, the particulate organic nitrate (PON) mass estimated from the AMS unit mass resolution (UMR) m/z 30:46 ratio (representing NO^+/NO_2^+ ratio, also referred to as the NO_x^+ ratio)⁷² and described in the supplementary information (Fig. S10), was observed higher in smouldering aerosol particles compared



to flaming (Fig. S10), averaging 75% of the total particulate nitrate mass in both combustion phases. The high percentage of PON in total particulate nitrate corresponds to the results of the CIMS particle phase data, where a large number of compounds with $O:N \geq 3$ possibly indicating organonitrogen compounds, were observed.

The higher mean O:C in flaming emissions observed in this study in comparison to smouldering burns is consistent with the observation of Reece *et al.*,⁷³ who that noticed an increase in O:C and decrease in H:C with improving combustion efficiency (obtainable in flaming burns) in their characterization of emissions from three different biomass cookstoves. This is consistent with the observations from the AMS data with similarly higher O:C in the flaming burn aerosol particles compared to smouldering.

Furthermore, the observed higher DBE/C and AI values in wood flaming emissions compared to smouldering indicates that flaming emissions may display greater aromaticity than smouldering emissions, possibly because of greater abundance of aromatic compounds in the flaming phase of wood than in the smouldering phase.⁶⁸ This is consistent with the observations of Kim *et al.*⁷⁴ who observed a greater mutagenic and lung toxicity potential in flaming phase emissions compared to smouldering from the combustion of several biomass fuels in a furnace.

5.0. Conclusions and implications

By studying controlled smoke injections into an aerosol chamber using the combined measurements of an iodide FIGAERO-CIMS and an AMS, we were able to chemically characterise the primary emissions of a stove, while controlling key variables such as fuel type and combustion phase. These experiments offered new insights into primary emissions and provide a chemical basis for subsequent studies on secondary chemistry, toxicology and interpretations of ambient observations. We observed differences in the aerosol particle composition between peat, leaves and wood fuels. However, contrary to the study of McClure *et al.*⁹ we found that the AMS f_{60} is a useful metric to distinguish between burning conditions, displaying higher values in the smouldering phase compare to flaming for both wood types. This is likely because McClure *et al.*⁹ studied a laboratory wildfire simulation, unlike this study based on stove emissions. Also, while previous studies establish the usefulness of levoglucosan or the AMS f_{60} metric in BBOA source apportionment studies, we found that air masses influenced by softwood flaming aerosols in the atmosphere may not be detected as BBOA because of low f_{60} , below the f_{60} background level. Trace elements like K^+ and Zn or a combination of levoglucosan and trace elements are recommended to provide more accurate results.

Consistent with previous observations, the oxygenated compounds dominated the stove emissions irrespective of fuel type and burn condition; and were higher in wood compared to leaves and peat. The smouldering burn had a higher oxygenated fraction than flaming in wood emissions, and thus may possess a higher SOA yield.⁶⁹ The dominance of $C_6H_6O_2$ signal in the gas phase was observed in all fuel types and burning condition along with $C_6H_{10}O_5$ in the particle phase (excluding softwood flaming). $C_6H_6O_2$ and $C_6H_{10}O_5$ are products of lignin and cellulose pyrolysis respectively and support the contribution of biomass burning to brown carbon emissions as noted by Ye *et al.*³⁹ Among the nitrogen-containing compounds, the results of this study indicate a dominance of reduced nitrogen and



organonitrogen compounds in the gas and particle phase respectively. The CHON fraction, on average were more pronounced in the particle-phase and contributed more to aromaticity in BB organic emissions than the oxygenated species. Wood flaming emissions displayed greater aromaticity in the particle phase due to a greater CHON fraction, compared to the smouldering phase. The results also demonstrate that leaves emissions display greater aromaticity than wood and peat because of the presence of CHON compounds with higher DBE/C and AI values.

The photochemical aging effects on the composition and characteristics of fresh smoke from stove emissions and the implication on health will be examined in subsequent publications. Also, insights from this study and aging effects will be explored in source apportionment studies of ambient data, and to aid the evaluation of the possible chemical and toxic effects of primary and secondary wood smoke in the atmosphere. Overall, this study enhances our comprehension of POA from a variety of biomass types and burning conditions and provides a critical basis for furthering our understanding of biomass burning related-SOA.

Author contributions

O.E.O, J.D.A, G.M, A.V, D.H and P.G contributed to conceptualization. O.E.O, A.V, D.H, and S.A.S contributed to investigation. O.E.O, A.V, T.B, S.A.S and H.W contributed to formal analysis. O.E.O wrote the original draft with contributions from A.V, T.J.B and J.D.A. All authors contributed to reviewing. O.E.O and J.D.A contributed to editing.

Conflicts of interest

There are no conflicts of interest to declare.

Data availability

The data supporting the findings of this study are partly included in a summarized table in the supplementary information. Additional data can be obtained from the corresponding author upon request.

Acknowledgements

The authors acknowledge the European Commission, Horizon 2020-Research and Innovation Framework Programme, H2020-INFRAIA-2020-1, Sustainable Access to Atmospheric Research Facilities (ATMO-ACCESS), for the funding of the Manchester Aerosol Chamber under Grant Agreement number:101008004. We also acknowledge the NERC HIP-TOX project (ref: NE/W002213/1, part of the Clean Air Strategic Priorities Fund). We thank the Tertiary Education Trust Fund (TETFund), Nigeria for the studentship of O.E.O, with sponsorship reference number TETF/ES/UNIV/DELTA STATE/TSAS/2019. S.A.S acknowledges studentship support from the Indonesia Endowment for Education (Lembaga Pengelola Dana Pendidikan, LPDP).

Footnote

‡ Now at: ° Univ. Paris Est Créteil and Université Paris Cité, CNRS, LISA, 94010 Créteil, France

References



1. K. Florou, D. K. Papanastasiou, M. Pikridas, C. Kaltsonoudis, E. Louvaris, G. I. Gkatzelis, D. Patoulas, N. Mihalopoulos and S. N. Pandis, The contribution of wood burning and other pollution sources to wintertime organic aerosol levels in two Greek cities. *Atmos. Chem. Phys.*, 2017, **17**, 3145–3163.
2. S. N. Pandis, K. Skylakou, K. Florou, E. Kostenidou, C. Kaltsonoudis, E. Hasa and A. A. Presto, Urban particulate matter pollution: a tale of five cities. *Faraday Discuss.*, 2016, **189**, 277–290.
3. R. L. Evans, D. J. Bryant, A. Voliotis, D. Hu, H. Wu, S. A. Syafira, O. E. Oghama, G. McFiggans, J. F. Hamilton, and A. R. Rickard, The importance of burning conditions on the composition of domestic biomass-burning organic aerosol and the impact of atmospheric ageing, *Atmos. Chem. Phys.*, 2025, **25**, 4367–4389.
4. B. J. Sumlin, Y. W. Heinson, N. Shetty, A. Pandey, R. S. Pattison, S. Baker, ... and R. K. Chakrabarty, UV–Vis–IR spectral complex refractive indices and optical properties of brown carbon aerosol from biomass burning, *J. Quant. Spectrosc. Radiat. Transfer*, 2018, **206**, 392–398.
5. T. Sigsgaard, B. Forsberg, I. Annesi-Maesano, A. Blomberg, A. Bölling, C. Boman & B. Brunekreef. Health impacts of anthropogenic biomass burning in the developed world, *Eur. Respir. J.*, 2015, **46**, 1577–1588.
6. X. Kong, C. M. Salvador, S. Carlsson, R. Pathak, K. O. Davidsson, M. Le Breton ... & J. B. Pettersson, Molecular characterization and optical properties of primary emissions from a residential wood burning boiler, *Sci. Total Environ.*, 2021, **754**, 142143.
7. GOV.UK, Emissions of Air Pollutants in the UK – Particulate Matter (PM10 and PM2.5), accessed 2023.
8. A. Bertrand, G. Stefanelli, E. A. Bruns, S. M. Pieber, B. Temime-Roussel, J. G. Slowik ... & N. Marchand, Primary emissions and secondary aerosol production potential from woodstoves for residential heating: Influence of the stove technology and combustion efficiency, *Atmos. Environ.*, 2017, **169**, 65–79.
9. C. D. McClure, C. Y. Lim, D. H. Hagan, J. H. Kroll and C. D. Cappa, Biomass-burning-derived particles from a wide variety of fuels – Part 1: Properties of primary particles, *Atmos. Chem. Phys.*, 2020, **20**, 1531–1547, <https://doi.org/10.5194/acp-20-1531-2020>.
10. International Energy Agency (IEA), Energy Policies of IEA Countries: Finland. 2013 Review, OECD, 2013.
11. C. Lin, D. Ceburnis, S. Hellebust, P. Buckley, J. Wenger, F. Canonaco ... & J. Ovadnevaite, Characterization of primary organic aerosol from domestic wood, peat, and coal burning in Ireland, *Environ. Sci. Technol.*, 2017, **51**, 10624–10632.
12. S. K. Akagi, R. J. Yokelson, C. Wiedinmyer, M. J. Alvarado, J. S. Reid, T. Karl, J. D. Crounse and P. O. Wennberg, Emission factors for open and domestic biomass burning for use in atmospheric models, *Atmos. Chem. Phys.*, 2011, **11**, 4039–4072, <https://doi.org/10.5194/acp-11-4039-2011>.
13. M. R. Alfarra, A. S. H. Prevot, S. Szidat, J. Sandradewi, S. Weimer, V. A. Lanz, D. Schreiber, M. Mohr and U. Baltensperger, Identification of the mass spectral signature of organic aerosols from wood burning emissions, *Environ. Sci. Technol.*, 2007, **41**, 5770–5777, <https://doi.org/10.1021/es062289b>.
14. E. A. Bruns, J. G. Slowik, I. El Haddad, D. Kilic, F. Klein, J. Dommen ... & A. S. Prévôt, Characterization of gas-phase organics using proton transfer reaction time-of-flight mass spectrometry: fresh and aged residential wood combustion emissions, *Atmos. Chem. Phys.*, 2017, **17**, 705–720.
15. B. H. Lee, F. D. Lopez-Hilfiker, C. Mohr, T. Kurtén, D. R. Worsnop and J. A. Thornton, An iodide-adduct high-resolution time-of-flight chemical-ionization mass spectrometer: Application to atmospheric inorganic and organic compounds, *Environ. Sci. Technol.*, 2014, **48**, 6309–6317, <https://doi.org/10.1021/es500362a>.
16. F. D. Lopez-Hilfiker, S. Iyer, C. Mohr, B. H. Lee, E. L. D'Ambro, T. Kurtén and J. A. Thornton, Constraining the sensitivity of iodide adduct chemical ionization mass spectrometry to multifunctional organic molecules using the collision limit and thermodynamic stability of iodide ion adducts, *Atmos. Meas. Tech.*, 2016, **9**, 1505–1512, <https://doi.org/10.5194/amt-9-1505-2016>.
17. M. Priestley, M. Le Breton, T. J. Bannan, K. E. Leather, A. Bacak, E. Reyes-Villegas ... & C. J. Percival, Observations of isocyanate, amide, nitrate, and nitro compounds from an anthropogenic biomass burning event using a ToF-CIMS, *J. Geophys. Res.: Atmos.*, 2018, **123**, 7687–7704.
18. J. H. Kroll, N. M. Donahue, J. L. Jimenez, S. H. Kessler, M. R. Canagaratna, K. R. Wilson, K. E. Altieri, L. R. Mazzoleni, A. S. Wozniak, H. Bluhm, E. R. Mysak, J. D. Smith, C. E. Kolb and D. R. Worsnop, Carbon oxidation state as a metric for describing the chemistry of atmospheric organic aerosol, *Nat. Chem.*, 2011, **3**, 133–139, <https://doi.org/10.1038/nchem.948>.
19. J. Liu, F. Zhang, W. Xu, Y. Sun, L. Chen, S. Li ... & R. Zhang, Hygroscopicity of organic aerosols linked to formation mechanisms, *Geophys. Res. Lett.*, 2021, **48**, e2020GL091683.
20. J. Tang, J. Li, T. Su, Y. Han, Y. Mo, H. Jiang, M. Cui, B. Jiang, Y. Chen, J. Tang, J. Song, ... & G. Zhang, Molecular compositions and optical properties of dissolved brown carbon in biomass burning, coal combustion, and vehicle emission aerosols illuminated by excitation–emission matrix spectroscopy and Fourier transform ion cyclotron resonance mass spectrometry analysis, *Atmos. Chem. Phys.*, 2020, **20**, 2513–2532, <https://doi.org/10.5194/acp-20-2513-2020>.
21. Y. Zeng, Y. Ning, Z. Shen, L. Zhang, T. Zhang, Y. Lei ... & J. Cao, The roles of N, S, and O in molecular absorption features of brown carbon in PM2.5 in a typical semi-arid megacity in Northwestern China, *J. Geophys. Res.: Atmos.*, 2021, **126**, e2021JD034791, <https://doi.org/10.1029/2021jd034791>.
22. M. Xie, X. Chen, M. D. Hays, M. Lewandowski, J. Offenberg, T. E. Kleindienst, A. L. Holder, Light absorption of secondary organic aerosol: composition and contribution of nitroaromatic compounds, *Environ. Sci. Technol.*, 2017, **51**, 11607–11616, <https://doi.org/10.1021/acs.est.7b03263>.
23. H. Jiang, J. Li, J. Tang, S. Zhao, Y. Chen, C. Tian, X. Zhang, B. Jiang, Y. Liao, G. Zhang, Factors influencing the molecular compositions and distributions of atmospheric nitrogen-containing compounds, *J. Geophys. Res. Atmos.*, 2022, **127**, e2021JD036284.
24. T. Faherty, H. Badri, D. Hu, A. Voliotis, F. D. Pope, I. Mudway, G. McFiggans, Hiptox—hazard identification platform to assess the health impacts from indoor and outdoor air pollutant exposures, through mechanistic toxicology: a single-centre double-blind human exposure trial protocol, *Int. J. Environ. Res. Public Health*, 2024, **21**, (3).
25. J. Chen, F. M. O. Jakob, A. Voliotis, H. Wu, S. A. Syafira, O. Oghama, Z. A. Kanji, Ice nucleation abilities and chemical characteristics of laboratory-generated and aged biomass burning aerosols, *Environ. Sci. Technol.*, 2025, **59**, 2575–2586, <https://doi.org/10.1021/acs.est.4c04941>.



26. R. L. Evans, D. J. Bryant, A. Voliotis, D. Hu, H. Wu, S. A. Syafira, O. E. Oghama, & A. R. Rickard, A semi-quantitative approach to nontarget compositional analysis of complex samples, *Anal. Chem.*, 2024, **96**, 18349–18358.
27. D. Liu, J. Whitehead, M. R. Alfara, E. Reyes-Villegas, D. V. Spracklen, C. L. Reddington, ... & J. D. Allan, Black carbon absorption enhancement in the atmosphere determined by particle mixing state, *Nat. Geosci.*, 2017, **10**, 184–188.
28. S. Li, D. Liu, D. Hu, S. Kong, Y. Wu, S. Ding, ... & D. Ding, Evolution of organic aerosol from wood smoke influenced by burning phase and solar radiation, *J. Geophys. Res. Atmos.*, 2021, **126**, e2021JD034534.
29. Y. Shao, Y. Wang, M. Du, A. Voliotis, M. R. Alfara, S. P. O'Meara, S. F. Turner, G. McFiggans, Characterisation of the Manchester Aerosol Chamber facility, *Atmos. Meas. Tech.*, 2022, **15**, 539–559.
30. Commission Regulation (EU) 2015/1185 of 24 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for solid fuel local space heaters (Text with EEA relevance), *Official Journal*, 2015, **L193**, 1–19, <http://data.europa.eu/eli/reg/2015/1185/oj>.
31. D. S. Kosyakov, N. V. Ul'yanovskii, T. B. Latkin, S. A. Pokryshkin, V. R. Berzhonskis, O. V. Polyakova, A. T. Lebedev, Peat burning—an important source of pyridines in the earth atmosphere, *Environ. Pollut.*, 2020, **266**, 115109.
32. J. Allan, S. Cottrill, S. Churchill, J. Jones, A. Lea-Langton, A. Price-Allison, R. Stewart, K. Tarnawski, A. Williams, R. Yardley, Emission factors for domestic solid fuels project: work package 1 report, 2023.
33. D. Hu, M. R. Alfara, K. Szpek, J. M. Langridge, M. I. Cotterell, C. Belcher, I. Rule, Z. Liu, C. Yu, Y. Shao, A. Voliotis, M. Du, B. Smith, G. Smallwood, P. Lobo, D. Liu, J. M. Haywood, H. Coe, and J. D. Allan, Physical and chemical properties of black carbon and organic matter from different combustion and photochemical sources using aerodynamic aerosol classification, *Atmos. Chem. Phys.*, 2021, **21**, 16161–16182, <https://doi.org/10.5194/acp-21-16161-2021>.
34. T. J. Bannan, M. Le Breton, M. Priestley, S. D. Worrall, A. Bacak, N. A. Marsden, ... & D. Topping, A method for extracting calibrated volatility information from the FIGAERO-HR-ToF-CIMS and its experimental application, *Atmos. Meas. Tech.*, 2019, **12**, 1429–1439.
35. F. D. Lopez-Hilfiker, C. Mohr, M. Ehn, F. Rubach, E. Kleist, J. Wildt, T. F. Mentel, A. Lutz, M. Hallquist, D. Worsnop, J. A. Thornton, A novel method for online analysis of gas and particle composition: description and evaluation of a filter inlet for gases and aerosols (FIGAERO), *Atmos. Meas. Tech.*, 2014, **7**, 983–1001.
36. M. Laborde, M. Schnaiter, C. Linke, H. Saathoff, K. H. Naumann, O. Möhler, ... & M. Gysel, Single particle soot photometer intercomparison at the AIDA chamber, *Atmos. Meas. Tech.*, 2012, **5**, 3077–3097.
37. M. J. Cubison, A. M. Ortega, P. L. Hayes, D. K. Farmer, D. Day, M. J. Lechner, ... & J. L. Jimenez, Effects of aging on organic aerosol from open biomass burning smoke in aircraft and laboratory studies, *Atmos. Chem. Phys.*, 2011, **11**, 12049–12064.
38. A. C. Aiken, P. F. Decarlo, J. H. Kroll, D. R. Worsnop, J. A. Huffman, K. S. Docherty, I. M. Ulbrich, C. Mohr, J. R. Kimmel, D. Sueper, Y. Sun, Q. Zhang, A. Trimborn, M. Northway, P. J. Ziemann, M. R. Canagaratna, T. B. Onasch, M. R. Alfara, A. S. H. Prevot, J. Dommen, J. Duplissy, A. Metzger, U. Baltensperger, and J. L. Jimenez, O/C and OM/OC ratios of primary, secondary, and ambient organic aerosols with high-resolution time-of-flight aerosol mass spectrometry, *Environ. Sci. Technol.*, 2008, **42**, 4478–4485, <https://doi.org/10.1021/es703009q>.
39. C. Ye, B. Yuan, Y. Lin, Z. Wang, W. Hu, T. Li, W. Chen, C. Wu, C. Wang, S. Huang, J. Qi, B. Wang, C. Wang, W. Song, X. Wang, E. Zheng, J. E. Krechmer, P. Ye, Z. Zhang, X. Wang, D. R. Worsnop, and M. Shao, Chemical characterization of oxygenated organic compounds in the gas phase and particle phase using iodide CIMS with FIGAERO in urban air, *Atmos. Chem. Phys.*, 2021, **21**, 8455–8478, <https://doi.org/10.5194/acp-21-8455-2021>.
40. M. Riva, P. Rantala, J. E. Krechmer, O. Peräkylä, Y. Zhang, L. Heikkinen, O. Garmash, C. Yan, M. Kulmala, D. Worsnop, and M. Ehn, Evaluating the performance of five different chemical ionization techniques for detecting gaseous oxygenated organic species, *Atmos. Meas. Tech.*, 2019, **12**, 2403–2421, <https://doi.org/10.5194/amt-12-2403-2019>.
41. L. Gao, A. Buchholz, Z. Li, J. Song, M. Vallon, F. Jiang, H. Saathoff, Volatility of secondary organic aerosol from β -caryophyllene ozonolysis over a wide tropospheric temperature range, *Environ. Sci. Technol.*, 2023, **57**, 8965–8974, <https://doi.org/10.1021/acs.est.3c02006>.
42. Y. Chen, M. Takeuchi, T. Nah, L. Xu, M. R. Canagaratna, H. Stark, ... N. L. Ng, Chemical characterization of secondary organic aerosol at a rural site in the southeastern US: insights from simultaneous high-resolution time-of-flight aerosol mass spectrometer (HR-ToF-AMS) and FIGAERO chemical ionization mass spectrometer (CIMS) measurements, *Atmos. Chem. Phys.*, 2020, **20**, 8421–8440, <https://doi.org/10.5194/acp-20-8421-2020>.
43. M. Desservetaz, M. Pikridas, I. Stavroulas, A. Bougiatioti, E. Liakakou, N. Hatzianastassiou, E. Bourtsoukidis, Emission of volatile organic compounds from residential biomass burning and their rapid chemical transformations, *Sci. Total Environ.*, 2023, **903**, 166592, <https://doi.org/10.1016/j.scitotenv.2023.166592>.
44. M. Du, A. Voliotis, Y. Shao, Y. Wang, T. J. Bannan, K. L. Pereira, ... & G. McFiggans, Combined application of online FIGAERO-CIMS and offline LC-Orbitrap mass spectrometry (MS) to characterize the chemical composition of secondary organic aerosol (SOA) in smog chamber studies, *Atmos. Meas. Tech.*, 2022, **15**, 4385–4406.
45. H. Jiang, J. Li, D. Chen, J. Tang, Z. Cheng, Y. Mo, ... & G. Zhang, Biomass burning organic aerosols significantly influence the light absorption properties of polarity-dependent organic compounds in the Pearl River Delta Region, China, *Environ. Int.*, 2020, **144**, 106079.
46. B. P. Koch, T. Dittmar, From mass to structure: an aromaticity index for high-resolution mass data of natural organic matter, *Rapid Commun. Mass Spectrom.*, 2006, **30**, 250, <https://doi.org/10.1002/rcm.7433>.
47. M. D. Jolleys, H. Coe, G. McFiggans, J. W. Taylor, S. J. O'Shea, M. Le Breton, M. W. Gallagher, Properties and evolution of biomass burning organic aerosol from Canadian boreal forest fires, *Atmos. Chem. Phys.*, 2015, **15**, 3077–3095, <https://doi.org/10.5194/acp-15-3077-2015>.
48. Y. Olsen, J. K. Nøjgaard, H. R. Olesen, J. Brandt, T. Sigsgaard, S. C. Pryor, ... & O. Hertel, Emissions and source allocation of carbonaceous air pollutants from wood stoves in developed countries: a review, *Atmos. Pollut. Res.*, 2020, **11**, 234–251.
49. G. Engling, J. He, R. Betha, and R. Balasubramanian, Assessing the regional impact of Indonesian biomass burning emissions based on organic molecular tracers and chemical mass balance modeling, *Atmos. Chem. Phys.*, 2014, **14**, 8043–8054.
50. J. Chen, S. H. Budisulistiorini, M. Itoh, W. C. Lee, T. Miyakawa, Y. Komazaki, L. D. Q. Yang, M. Kuwata, Water uptake by fresh Indonesian peat burning particles is limited by water-soluble organic matter, *Atmos. Chem. Phys.*, 2017, **17**, 11591–11604.



51. C. Xu, X. Zhang, Z. Hussein, P. Wang, R. Chen, Q. Yuan, ... & S. G. Gouda, Influence of the structure and properties of lignocellulose on the physicochemical characteristics of lignocellulose-based residues used as an environmentally friendly substrate, *Sci. Total Environ.*, 2021, **790**, 148089.
52. S. Weimer, M. R. Alfara, D. Schreiber, M. Mohr, A. S. Prévôt, and U. Baltensperger, Organic aerosol mass spectral signatures from wood-burning emissions: influence of burning conditions and wood type, *J. Geophys. Res. Atmos.*, 2008, **113**, D10.
53. T. Lee, A. P. Sullivan, L. MacK, J. L. Jimenez, S. M. Kreidenweis, T. B. Onasch, D. R. Worsnop, W. Malm, C. E. Wold, W. M. Hao, and J. L. Collett, Chemical smoke marker emissions during flaming and smouldering phases of laboratory open burning of wildland fuels, *Aerosol Sci. Technol.*, 2010, **44**, 9, <https://doi.org/10.1080/02786826.2010.499884>.
54. A. C. Aiken, D. Salcedo, M. J. Cubison, J. A. Huffman, P. F. DeCarlo, I. M. Ulbrich, K. S. Docherty, D. Sueper, J. R. Kimmel, D. R. Worsnop, A. Trimborn, M. Northway, E. A. Stone, J. J. Schauer, R. M. Volkamer, E. Fortner, B. de Foy, J. Wang, A. Laskin, V. Shutthanandan, J. Zheng, R. Zhang, J. Gaffney, N. A. Marley, G. Paredes-Miranda, W. P. Arnott, L. T. Molina, G. Sosa, and J. L. Jimenez, Mexico City aerosol analysis during MILAGRO using high resolution aerosol mass spectrometry at the urban supersite (T0) – Part 1: fine particle composition and organic source apportionment, *Atmos. Chem. Phys.*, 2009, **9**, 6633–6653, <https://doi.org/10.5194/acp-9-6633-2009>.
55. K. S. Docherty, E. A. Stone, I. M. Ulbrich, P. F. DeCarlo, D. C. Snyder, J. J. Schauer, R. E. Peltier, R. J. Weber, S. M. Murphy, J. H. Seinfeld, B. D. Grover, D. J. Eatough, and J. L. Jimenez, Apportionment of primary and secondary organic aerosols in Southern California during the 2005 Study of Organic Aerosols in Riverside (SOAR-1), *Environ. Sci. Technol.*, 2008, **42**, 7655–7662, <https://doi.org/10.1021/es8008166>.
56. D. E. Young, J. D. Allan, P. I. Williams, D. C. Green, R. M. Harrison, J. Yin, M. J. Flynn, M. W. Gallagher, and H. Coe, Investigating a two-component model of solid fuel organic aerosol in London: processes, PM1 contributions, and seasonality, *Atmos. Chem. Phys.*, 2015, **15**, 2429–2443, <https://doi.org/10.5194/acp-15-2429-2015>.
57. J. B. Gilman, B. M. Lerner, W. C. Kuster, P. D. Goldan, C. Warneke, P. R. Veres, J. M. Roberts, J. A. de Gouw, I. R. Burling, and R. J. Yokelson, Biomass burning emissions and potential air quality impacts of volatile organic compounds and other trace gases from fuels common in the US, *Atmos. Chem. Phys.*, 2015, **15**, 13915–13938, <https://doi.org/10.5194/acp-15-13915-2015>.
58. C. E. Stockwell, P. R. Veres, J. Williams and R. J. Yokelson, 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, *Atmos. Chem. Phys.*, 2015, **15**, 845–865.
59. J. Pohleven, M. D. Burnard and A. Kutnar, Volatile organic compounds emitted from untreated and thermally modified wood—a review, *Wood Fiber Sci.*, 2019, **51**, 231–254.
60. W. Zhou, W. Xu, Z. Li, L. Lei, Y. Li, J. Sun, ... & Y. Sun, Molecular characterization of gaseous organic acids and nitrogen-containing compounds from crop straw and wood burning, *J. Geophys. Res. Atmos.*, 2024, **129**, e2023JD040568.
61. B. R. Simoneit, Biomass burning—a review of organic tracers for smoke from incomplete combustion, *Appl. Geochem.*, 2002, **17**, 129–162.
62. A. Iglovikov and A. Motorin, Composition of organic matter in peat soils of the northern trans-Urals depending on groundwater level, in *E3S Web Conf.*, 2019, vol. 135, p. 01004.
63. C. Mohr, F. D. Lopez-Hilfiker, P. Zotter, A. S. H. Prévôt, L. Xu, N. L. Ng, S. C. Herndon, L. R. Williams, J. P. Franklin, M. S. Zahniser, D. R. Worsnop, W. B. Knighton, A. C. Aiken, K. J. Gorkowski, M. K. Dubey, J. D. Allan and J. A. Thornton, Contribution of nitrated phenols to wood burning brown carbon light absorption in Detling, United Kingdom during winter time, *Environ. Sci. Technol.*, 2013, **47**, 6316–6324, <https://doi.org/10.1021/es400683v>.
64. M. Xie, X. Chen, M. D. Hays and A. L. Holder, Composition and light absorption of N-containing aromatic compounds in organic aerosols from laboratory biomass burning, *Atmos. Chem. Phys.*, 2019, **19**, 2899–2915, <https://doi.org/10.5194/acp-19-2899-2019>.
65. Y. Liang, R. A. Wernis, K. Kristensen, N. M. Kreisberg, P. L. Croteau, S. C. Herndon and A. H. Goldstein, Gas–particle partitioning of semivolatile organic compounds when wildfire smoke comes to town, *Atmos. Chem. Phys.*, 2023, **23**, 12441–12454, <https://doi.org/10.5194/acp-23-12441-2023>.
66. Y. Cai, C. Ye, W. Chen, W. Hu, W. Song, Y. Peng ... & X. Wang, The important contribution of secondary formation and biomass burning to oxidized organic nitrogen (OON) in a polluted urban area: insights from in situ FIGAERO-CIMS measurements, *Atmos. Chem. Phys. Discuss.*, 2023, 1–30.
67. L. E. Hatch, W. Luo, J. F. Pankow, R. J. Yokelson, C. E. Stockwell and K. C. Barsanti, Identification and quantification of gaseous organic compounds emitted from biomass burning using two-dimensional gas chromatography-time-of-flight mass spectrometry, *Atmos. Chem. Phys.*, 2015, **15**, 1865–1899, <https://doi.org/10.5194/acp-15-1865-2015>.
68. G. Stefenelli, J. Jiang, A. Bertrand, E. A. Bruns, S. M. Pieber, U. Baltensperger ... & I. El Haddad, Secondary organic aerosol formation from smouldering and flaming combustion of biomass: a box model parametrization based on volatility basis set, *Atmos. Chem. Phys.*, 2019, **19**, 11461–11484.
69. R. Volkamer, J. L. Jimenez, F. San Martini, K. Dzepina, Q. Zhang, D. Salcedo, M. T. Molina, D. R. Worsnop and M. J. Molina, Secondary organic aerosol formation from anthropogenic air pollution: rapid and higher than expected, *Geophys. Res. Lett.*, 2006, **33**, L17811, <https://doi.org/10.1029/2006GL026899>.
70. M. Evtugina, C. Alves, A. Calvo, T. Nunes, L. Tarelho, M. Duarte, S. O. Prozil, D. V. Evtuguin and C. Pio, VOC emissions from residential combustion of Southern and mid-European woods, *Atmos. Environ.*, 2014, **83**, 90–98.
71. J. C. Ditto, J. Machesky and D. R. Gentner, Analysis of reduced and oxidized nitrogen-containing organic compounds at a coastal site in summer and winter, *Atmos. Chem. Phys.*, 2022, **22**, 3045–3065.
72. D. K. Farmer, A. Matsunaga, K. S. Docherty, J. D. Surratt, J. H. Seinfeld, P. J. Ziemann and J. L. Jimenez, Response of an aerosol mass spectrometer to organonitrates and organosulfates and implications for atmospheric chemistry, *Proc. Natl. Acad. Sci. U. S. A.*, 2010, **107**, 6670–6675.
73. S. M. Reece, A. Sinha and A. P. Grieshop, Primary and photochemically aged aerosol emissions from biomass cookstoves: chemical and physical characterization, *Environ. Sci. Technol.*, 2017, **51**, 9379–9390.
74. Y. H. Kim, S. H. Warren, Q. T. Krantz, C. King, R. Jaskot, W. T. Preston ... & M. I. Gilmour, Mutagenicity and lung toxicity of smouldering vs. flaming emissions from various biomass fuels: implications for health effects from wildland fires, *Environ. Health Perspect.*, 2018, **126**, 017011, <https://doi.org/10.1289/ehp2200>.



Variations in oxygenated and nitrogen-containing primary organic compounds by fuel type and burning condition in stove emissions

View Article Online
DOI: 10.1039/D5EA00080G

Osayomwanbor E. Oghama ^{*a}, Aristedis Voliotis ^{a,b}, Thomas J. Bannan ^a, Sara A. Syafira ^a, Dawei Hu ^a, Huihui Wu ^{a,c}, Peter Gallimore ^a, Gordon McFiggans ^a, Hugh Coe ^{a,b}, James D. Allan ^{*a,b}

Data availability

The data supporting the findings of this study are partly included in a summarized table in the supplementary information. Additional data can be obtained from the corresponding author upon request.

