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Comparative review of laboratory approaches for simulating and characterizing aerosol emissions from open biomass burning

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Open biomass burning (BB) is a major global source of atmospheric particulate matter, yet laboratory studies often report divergent aerosol aging outcomes that are difficult to compare across experiments. While this variability is frequently attributed to fuel properties or oxidation conditions, the influence of the laboratory facility architecture and smoke-conditioning design has not been systematically evaluated. To address this gap, this review develops a structured framework for comparing laboratory BB aerosol facilities, informed by an analysis of 39 facilities reported in the literature. This framework integrates a nine-category structural classification with a concise encoding of consistently reported smoke-conditioning features, and it is complemented by a working hierarchy to evaluate the relative importance of facility-conditioning factors. Organic aerosol mass enhancement is employed as a representative and widely reported outcome metric to evaluate and illustrate the interpretive value of the framework, using a combination of qualitative synthesis and semi-quantitative trend analysis. The analysis indicates that facility design choices, particularly those governing smoke handling and conditioning prior to the first measurement, which define the initial smoke state, systematically influence the reported OA mass enhancement and can, in many cases, exert a stronger effect than the aging environment itself. Beyond OA mass enhancement, the framework clarifies key design trade-offs among existing laboratory configurations, improves the cross-study comparability, and provides practical guidance for the design and interpretation of future BB aerosol experiments.

Environmental significance

This review provides insight into how the interpretation of organic aerosol (OA) mass evolution from different biomass burning studies can be influenced by the design and configuration of laboratory facilities themselves. By systematically comparing thirty-nine facilities worldwide, it identifies how variations in combustion setup, dilution, sampling, and smoke-transfer systems can lead to divergent experimental outcomes even under similar atmospheric conditions. Understanding these methodological sources of variability is essential for improving the comparability of laboratory and field results, enhancing the reliability of OA evolution data used in atmospheric models, and ultimately refining estimates of biomass burning impacts on air quality and climate.

1. Introduction

Many studies have reported that open biomass burning (BB) is a major source of pollutants around the world.[10–20] This results in many adverse effects on both the environment and living organisms, including humans living around the affected area. Consequently, the properties of these pollutants, either in the gas or particle phase, have become a concern in many studies. Equally, the transformation of the properties of these pollutants as they age, along with the driving parameters, has attracted increasing attention recently. Meanwhile, answering the research questions that emerged from these concerns is challenging to achieve once pursued through direct field-scale research studies.[1] This is due to the varying parameters and factors that could occur in real biomass burning events. This certainly includes a variation in the atmospheric oxidation stage and time scales. One approach to overcome the limitations of field-scale studies is through laboratory-scale studies on biomass burning smoke.

Laboratory-scale studies on biomass burning smoke can offer a more comprehensive, structured, and in-depth analysis of the experimental investigation results. Any connection

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between the smoke properties can be more independently analysed in these studies. This is mainly attributed to the reduction in the complexity of the parameters and controlled conditions. These unique features of laboratory-scale studies can apply to the whole period of experiments. The whole period refers to not only the smoke dark or photoaging period, if conducted, but also other periods. For instance, the fuel burning period, smoke dispersion period and dilution period. The importance of laboratory-scale studies for more general types of atmospheric chemistry, *i.e.*, not specifically about biomass burning aerosol, was argued in a dedicated article on this topic.[2] However, despite the benefit of conducting laboratory-scale studies on biomass burning smoke, another issue arises. Previous review studies[3,4,19,20] have also shown that the OA mass evolution inferred from laboratory chamber experiments can differ substantially from that inferred from the field observations of BB plumes, particularly in terms of the net OA enhancement ratio (OAER) and the balance between evaporation and secondary formation. Over the past decade, many BB laboratory studies have characterised OA transformation under dark and photo-oxidative ageing conditions, often reporting results using OAER. Across these studies, the OAER values span nearly the full range, from substantial net OA production to marked evaporation, even for ostensibly comparable fuels and experimental setups, underscoring the complexity of BB aerosol evolution.[3–6,16,19,21,22]

When analysed across existing literature,[3–6] several consistent themes emerge. Combustion-related factors such as fuel composition, burning phase, and combustion efficiency determine the volatility and chemical character of primary emissions. Dilution dynamics and entrainment behaviour strongly influence early gas–particle repartitioning and either suppress or enhance apparent OA mass changes. Ageing conditions, including oxidant exposure and the balance between dark and photo-oxidative pathways, govern whether OA tends toward evaporation, functionalisation, or secondary formation during processing. In parallel, environmental and analytical factors, including chamber surface-to-volume ratio, wall losses, temperature and humidity, light intensity, and baseline definition, introduce additional variability into reported OA outcomes. Together, these themes describe the major process-level and analytical drivers of BB OA evolution.

However, an additional dimension remains comparatively underexplored in previous review works,[3–6] which is the influence of the laboratory facility architecture and smoke-conditioning design. BB laboratories differ in their structural configuration, including batch *versus* flow operation, integration or separation of combustion and ageing units, mode and timing of dilution, and whole-flow *versus* subsampling

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approaches, and in operational choices such as oxidant introduction, gas-removal tools, and transfer-line conditioning. These architectural and conditioning elements shape the chemical and physical state of BB emissions prior to ageing and therefore may systematically influence OAER, yet they have not been analysed previously into a unified interpretive framework. A previously published book provides a consolidated overview of best-practice knowledge on the design, operation, and interpretation of only the atmospheric simulation chambers—along with their strengths and inherent limitations in representing atmospheric processes—without focusing on applications to biomass-burning studies.[8]

Furthermore, substantial variability can arise within a single facility. Tkacik *et al.*[15] showed that repeated burns of the same fuel, conducted under nominally identical conditions, can still yield widely varying OAER values, ranging from net OA loss to clear enhancement. These burn-to-burn differences reflect variations in combustion temperature, oxygen availability, mixing, and other micro-scale combustion dynamics. This variability sets a practical lower bound on the scatter expected in any cross-facility comparison. Accordingly, the influence of facility design should be viewed as an additional layer that may amplify or dampen OA evolution, rather than as a replacement for combustion-driven variability.

This review complements existing fuel-centric syntheses and OAER-focused analyses by centring on facility-defined pathways and smoke-conditioning practices as key interpretive dimensions. We develop a structured framework for comparing laboratory biomass-burning aerosol facilities, informed by an analysis of 39 facilities reported in the literature. The framework integrates a nine-category structural classification with a concise encoding of consistently reported conditioning features and incorporates a working hierarchy to assess the relative importance of facility-conditioning factors across laboratory systems. Organic aerosol mass enhancement is employed as a representative and widely reported outcome metric to illustrate the interpretive value of the framework. Used as a demonstrative lens rather than the sole focus, OAER highlights how differences in facility configuration and early smoke handling shape reported experimental outcomes. Beyond OAER, the framework clarifies design trade-offs among laboratory configurations, improves cross-study comparability, and distils key considerations for the design and interpretation of future biomass-burning aerosol experiments.

2. Methods

2.1. Literature selection

This review was compiled through a structured search of peer-reviewed journal articles and their corresponding SI that described biomass-burning aerosol laboratory facilities. Publications were retrieved using combinations of keywords such as biomass burning laboratory, smog chamber, combustion facility, and aerosol aging. The search covered studies published up to 2023. In total, initially 30 facilities located in 26 countries met these criteria. Thirteen of them had previously been listed by a published article in 2015,[7] while the remaining facilities were identified from literature published between 2015 and 2023. Facility information was extracted, categorized, and tabulated to ensure consistency.

Upon the peer review process with the Environmental Science: atmospheres journal, the search was updated up to 2025, last updated on 22 December 2025. For the update from 2024, the year filter "since 2024" and the set of search keywords: "biomass burning", "laboratory", "combustion source" were used in Google Scholar in one run. This search returned 346 articles, of which 16 were found relevant and selected, with the note that the fully checked articles are only fully published journal articles, not preprint journal articles, conference articles, and degree final project reports/theses/dissertations. Among the 16 articles, nine different facilities were added, while the other 7 articles used the same facilities as those already listed either in the earlier listed 30 facilities or the nine recently added facilities. The inclusion criteria of facilities are presented in Section 2.1.1.

A list of the reviewed facilities can be found in the SI, Sections 1: parts A, B, and C. A compiled, detailed reference-based discussion of each facility is presented in the SI, Section 8. Meanwhile, the main table summarizing all the key or most important/relevant information for each facility, especially for the OAER semi-quantitative and qualitative investigation, is presented in the SI, Section 2: Table S1 and S2. Another table containing information on the facilities is presented in the SI, last section (Section 8), Table S3.

2.1.1 Identification and inclusion of biomass-burning aerosol facilities.

The identification and inclusion of biomass-burning (BB) aerosol facilities followed the protocol below.

2.1.1.1 Aerosol source definition. BB aerosol sources were classified into two non-exclusive categories:

(1) Researcher-operated biomass combustion sources, including, but not limited, to residential wood stoves, tube or quartz furnaces, fire propagation apparatus (FPA), open or semi-open burning setups, and combustion chambers or rooms. If authors explicitly generated BB aerosol themselves, the source was treated as defined, even if it was briefly described.

(2) Biomass-burning-rich ambient or near-source air, including ambient air dominated by BB influence or near-field BB plumes sampled directly from the environment.

Studies using residential stoves were eligible only when the stove was explicitly operated as part of a controlled experimental setup defining a BB aerosol source and pathway. Studies employing stoves as actual household appliances for heating or cooking within real residences, without a facility-defined experimental context, were excluded.

2.1.1.2 Facility-defined aerosol handling pathway. For each study, it was determined whether the BB aerosol was processed through a facility-defined handling pathway, such as a stack, hood, duct, or controlled inlet; a dilution tunnel or chamber; a storage or mixing chamber with defined residence time; a smog chamber; or an oxidation flow reactor (OFR/PAM).

Standalone samplers (*e.g.* filters or probes without controlled residence time or ageing) were not considered facility-defined pathways.

Instrument placement was not required to be at the exhaust stack; instruments could be located at any explicitly defined outlet or downstream point of the combustion source within the BB facility.

2.1.1.3 Inclusion logic. A study was classified as a BB aerosol facility study if either of the following conditions was satisfied:

Condition A: a researcher-operated biomass combustion source was present, with or without subsequent facility processing.

Condition B: biomass-burning-rich ambient or near-source air was introduced into a facility-defined aerosol-handling pathway.

If neither condition was met, the study was excluded from the facility analysis.

This screening criterion ensured the inclusion of laboratory- and facility-based BB studies while excluding purely observational ambient studies lacking defined aerosol pathways, as well as non-facility-based household combustion activities conducted under real-use domestic conditions (*e.g.*, cooking and heating), rather than within dedicated controlled experimental setups.

2.2 Data compilation and semi-quantitative analysis

2.2.1 Compilation of OAER and facility information. Detailed information on the OA mass enhancement ratios reported for individual facilities was compiled in Table S1 and S2, SI. Section 2. This table only includes studies that explicitly investigated aging-driven OA mass changes and provided sufficient methodological details to identify both facility design and pre-aging or pre-measurement treatments. For clarity, the terms "increase" and "decrease" in the tables denote the net change in organic aerosol mass relative to its value at the time point defined as the start of the aging process.

Table S1, SI: Section 2 summarizes the key conditioning features applied before aging and/or measurement, including the five factors represented by the 4-Letter-1-Number comparison codes and transfer-line conditions. When numerical values are reported (*e.g.*, dilution ratios, residence times, and oxidant exposure), they are taken directly from the source publications and reflect experimental conditions rather than derived quantities.

In addition to facility-conditioning information, Table S1 documents the fuel type, burning phase, and combustion-source characteristics for each experiment. These variables were not controlled in the present analysis but were retained to provide contextual information and enable more targeted comparisons in future work. In total, the OAER information was compiled from 11 laboratory facilities described across 20 peer-reviewed articles, yielding initially 42 distinct OAER observation points but only 40 of them reported exact numeric OAER values, and thus selected for semi-quantitative analysis.

The number of OAER observations exceeds the number of facilities because (i) several facilities are reported in more than one article and (ii) individual studies often report multiple OAER values corresponding to different and conditions (*e.g.*, fuel type, oxidation regime, and aging duration). Therefore, each OAER observation was treated as a separate data point, while inheriting a single facility-level conditioning code, consistent with the semi-quantitative and comparative nature of the analysis. This approach does not imply statistical independence between observations from the same facility but is intended to capture the range of OAER outcomes reported under different experimental configurations for comparative trend analysis rather than formal inference. Fig. S1, SI: Section 2 illustrates the distribution of OAER outcomes based on the compiled dataset.

2.2.2. Semi-quantitative analysis of the tested OAER influencing factors. Alongside the qualitative comparison, a simple semi-quantitative check was conducted to examine whether the eight facility-conditioning factors identified in Section. 3 show measurable associations with the reported organic aerosol mass enhancement ratios (OAER). The OAER values compiled from the reviewed studies were analysed using a linear model of the form:

$$\text{Log(OAER)} = \beta 0 + \beta 1(\text{aging\_mode}) + \beta 2(\text{OFR}) + \beta 3(\text{multi\_stage}) + \beta 4(\text{sub\_sampling}) + \beta 5(\text{early\_gas\_removal}) + \beta 6(\text{line\_conditioning}) + \beta 7(\text{recondensation}) + \beta 8(\text{mixing}) + \varepsilon$$

The variables correspond to the facility-conditioning factors defined conceptually in Section. 3, with categorical settings treated as indicator values. The operational coding of each factor used in the regression analysis is described in detail in SI: Section 4.

Given the diversity of experimental designs and the uneven reporting across studies, this analysis is not intended to yield precise statistical coefficients. Rather, it provides a structured means to assess whether the direction and relative magnitude of the estimated effects are consistent with the proposed working hierarchy of OAER-relevant factors. Therefore, the results are interpreted as supporting evidence rather than as formal statistical inference.

To enable a comparison of the relative influence of factors coded on different scales, factor dominance was assessed using normalized effect metrics rather than raw regression coefficients. Relative dominance was evaluated based on the implied OAER change across the coded range of each factor, allowing comparison across binary and ordinal encodings.

Given the heterogeneity and incomplete reporting across studies, this coding scheme is necessarily simplified. It is intended to enable a consistent and transparent comparison across facilities rather than to provide a detailed physical representation of each system.

3. General background & high-level grouping of factors affecting the organic aerosol (OA) mass enhancement ratio (OAER)

Laboratory-based studies on biomass-burning aerosols have expanded significantly over the past two decades, resulting in a diverse range of experimental facilities worldwide. Early developments focused primarily on quantifying fresh emissions for emission inventories, whereas recent designs incorporate controlled aging systems, advanced dilution methods, and environmental controls to better simulate atmospheric processing.

3.1 Historical development, scope, geographic distribution, and trends

Thirteen facilities described in a SI table in ref. 7 represent the first generation of biomass-burning laboratories. These were primarily located in North America and Europe, and their designs emphasized stack-based sampling of fresh emissions. By targeting only the fresh emissions, studies during this period, *i.e.*, before 2015, primarily focused on emission-factor inventories and emphasized physicochemical and optical characterization of near-source smoke.

Since 2015, at least 17 additional facilities have been constructed across Europe, North America, and Asia, many of which include oxidation flow reactors (OFRs), large-volume smog chambers, and dual-chamber configurations to explore both dark and photo-oxidative aging. Overall, the geographic distribution of facilities is concentrated in Europe (*e.g.*, PSI, UEF, and FORTH) and North America (*e.g.*, DRI, NCAT, and CMU), with emerging programs in Asia. Facility designs have shifted from basic stack experiments toward integrated systems capable of simulating multi-day atmospheric aging, incorporating precise humidity and temperature control and enabling repeated, highly reproducible experiments.

3.2. High-level grouping of factors affecting the organic aerosol (OA) mass enhancement ratio (OAER)

Table 1 summarizes three broad groups of factors that influence the organic aerosol mass enhancement ratio (OAER) reported in laboratory biomass-burning experiments. The first group reflects inherent combustion-source variability, the second group captures environmental and analytical context, and the third group comprises facility-design and sampling factors, which are the primary focus of this review. Within this last group, eight conditioning-related factors are identified, five of which are summarized using the 4-Letter-1-Number framework introduced later in Section 4.2.

The differences in OAER across facilities can be interpreted in the context of well-established volatility-dependent partitioning and oxidation processes. Dilution history, evaporation of semi-volatile materials, and the nature and intensity of oxidant exposure are known to influence OA mass evolution through shifts in gas–particle partitioning and changes in the balance between functionalization and fragmentation pathways. These mechanisms provide the physical basis for why facility design and conditioning choices can lead to divergent OAER behaviour, even when similar fuels or ageing approaches are used.

As SOA formation ultimately depends on the emission profiles of both the particle and gas phases of biomass-burning smoke, factors such as fuel type and burning phase play an important role in determining absolute OAER values. This sensitivity persists despite field observations reporting weaker fuel-type- and combustion-phase-dependent variability in OA mass evolution than in OA loading.[23] In the present analysis, these variables were not controlled but were documented (Table S1, SI: Section 2) to enable later, more targeted comparisons. Variations in combustion source type were treated in the same manner.

Environmental and analytical factors, including temperature, relative humidity, light intensity, and chamber wall effects, are also known to influence SOA formation. However, these parameters were not extracted or coded for comparative testing in this review, which was designed to isolate the effects of facility-design and sampling-related variables summarized by the 4-Letter-1-Number framework and by the detailed handling

Table 1 Hierarchical grouping of factors influencing laboratory biomass-burning aerosol studies, especially the OA mass net enhancement ratio

Group	Category meaning	Examples/citations/notes
A Combustion source factors	Inherent variability from the burning process itself; not part of the laboratory facility design but drives input composition	Fuel type, burning phase, combustion efficiency, and emission temperature (not discussed in detail in this review; see field/lab coupling studies)[3,4]
B Environmental and analytical context factors	Experimental or analytical context conditions that influence SOA formation but are not structural facility features	Temperature, RH, light intensity, chamber S/V ratio, wall loss correction, and SOA density assumption, as summarized by Kim *et al.* (2024)[6]
C Facility-design and sampling factors (current review focus)	Configurable features that define how emissions are handled and measured within laboratory facilities	The 4-letter-1-Number framework + detailed SVOC transfer handling (factor numbers 6 and 7) + mixing 1. Oxidant/photochemistry control 2. Residence time 3. Dilution architecture 4. Whole *vs.* sub-sampling 5. Early organic-gas removal tools 6. Transfer-line heating/insulation 7. Facilitated organic gas recondensation before measurement 8. (Potential-added factor) mixing

of semi-volatile organic compounds (factors 6 and 7), along with mixing as a suspected minor influencing factor. Therefore, the environmental conditions were treated as part of the operational context of each facility rather than as variables under direct comparison.

This approach allows an assessment of whether differences in facility configuration, particularly those related to early SVOC handling, are sufficiently large to explain the cross-study variability in OAER, and whether they justify more constrained, fuel-specific analyses in future work.

4. Framework for cross-facility comparison

Biomass-burning (BB) facilities differ widely in their physical construction, smoke-handling strategies, and operational conditioning settings. To systematically compare their influence on organic aerosol evolution, this review applies a three-layer framework:

(1) Nine facility categories, which describe the physical engineering architecture of each system.

(2) The 4-Letter-1-Number (4L1N) code, which summarizes the operational conditioning settings used in each experiment.

(3) A tiered hierarchy of OAER-relevant factors, which identifies the relative mechanistic importance of different design and conditioning elements.

Together, these components distinguish what a facility is (architecture), how an experiment was run (conditioning), and which factors matter most for OA mass enhancement (OAER).

4.1. Facility architecture: the nine structural categories

The first layer of the framework classifies each BB facility according to its physical engineering design, reflecting the hardware architecture of the facility, and thus what the system is, independent of how any specific experiment is configured. The nine categories (Fig. 1) describe fixed structural attributes, including:

- How the combustion source is positioned relative to the measurement system.

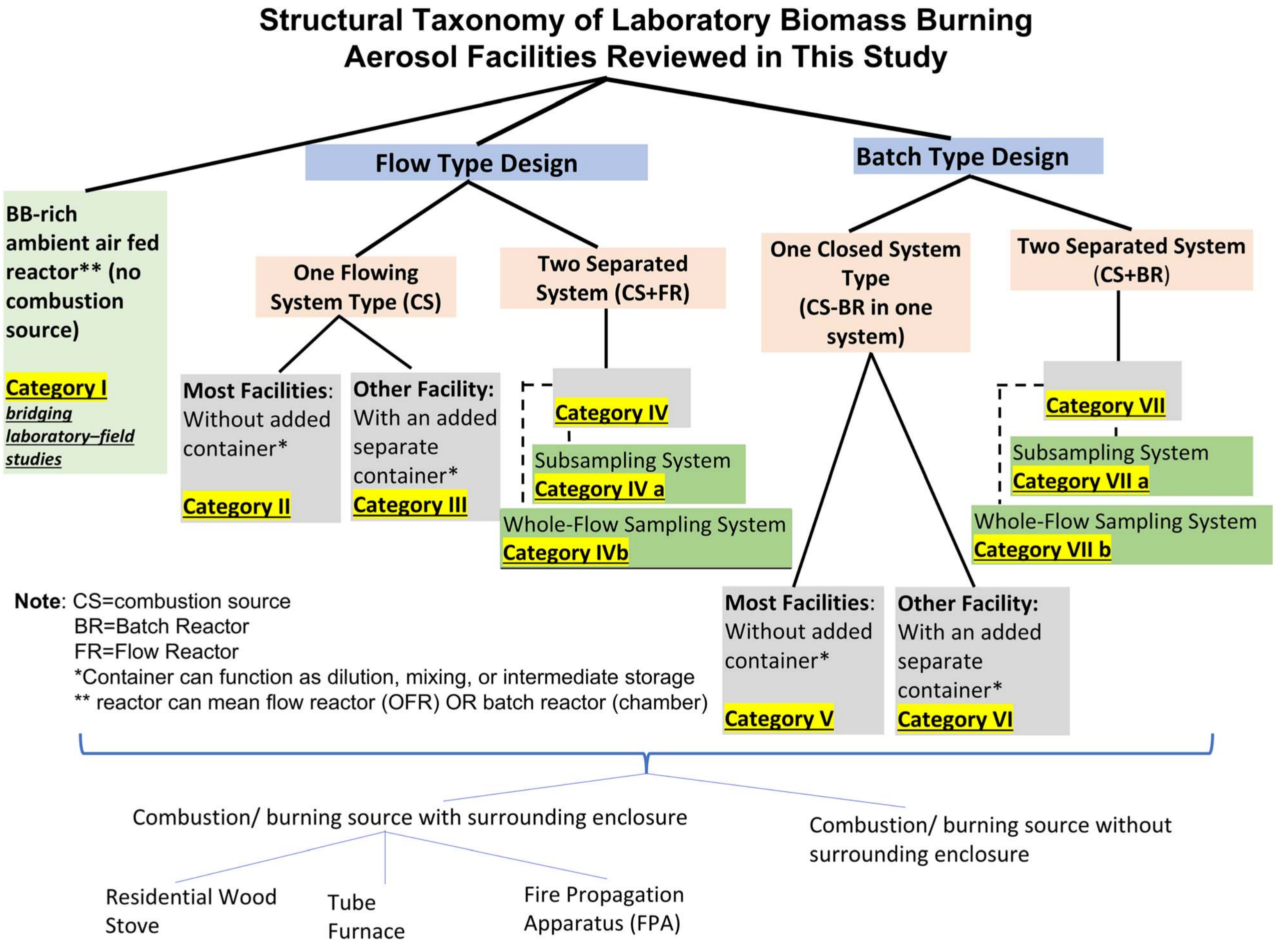

Fig. 1 Structural taxonomy of laboratory biomass-burning study facilities reviewed up to 2025. Facilities are classified into nine architectural categories based on flow or batch operation, system separation, and sampling configuration. These nine categories collapse into seven core facility architectures, with categories IV and VII further subdivided into 'a' and 'b' variants to distinguish subsampling *versus* whole-part sampling configurations applied within otherwise identical architectural designs. Roman-numeral categories denote facility-level architecture, while lettered subcategories indicate sampling configuration and do not represent additional structural modification.

Table 2 Limitations and advantages of each category

Categories	Advantages	Limitations
Category I–no combustion source + (mobile/portable) reactor + measuring instruments	• Ageing steps (dark or photo) can be added in the chamber • Sample can be real ambient smoke together with other pollutants *Other advantages depend on chamber/OFR	• Ambient conditions vary, which reduces repeatability • No direct control over the combustion source *Other limitations depend on chamber/OFR
Category II–combustion source-flowing stack + measuring instruments	• Very short residence time keeps the smoke close to its fresh state • Suitable for fast-response instruments	• Changing smoke conditions in flow systems limit long-scan measurements • No ageing step is possible because there is no chamber or reactor
Category III–combustion source-flowing stack + dilution tool/storage chamber + measuring instruments	• Very short upstream residence time keeps the emissions close to fresh • Dilution helps manage high concentrations before measurement • A storage container can be used for ageing steps if needed	• The chamber size affects wall loss, which may lower particle and gas levels in the sample • Longer residence time allows some changes before measurement • Additional containers add extra wall surfaces
Category IVa–combustion source-flowing stack + oxidation flow reactor (OFR) + measuring instruments(Connection through subsampling)	• Short upstream residence time maintains fresh smoke conditions before entering the OFR • The OFR provides rapid ageing • Subsampling makes it possible to take a controlled portion of the exhaust	• Changing smoke conditions inside the OFR limit long-scan measurements • Subsampling can produce mixing differences compared to whole-flow sampling • Transfer lines may lose SVOCs if not conditioned
Category IVb–combustion source-flowing stack + oxidation flow reactor (OFR) + measuring instruments (whole-flow sampling)	• Short upstream residence time maintains fresh smoke conditions before OFR treatment • The OFR provides rapid ageing • Whole-flow sampling gives a more representative sample	• Changing smoke conditions inside the OFR limit long-scan measurements • Whole-flow setups require larger and more complex plumbing • Transfer lines may lose SVOCs if not conditioned
Category V–combined burning and smoke storage chamber + measuring instruments	• Stable chamber conditions allow the use of long-scan instruments • Ageing steps (dark or photo) can be added • No transfer line between burning and storage reduces particle and gas losses	• The chamber size affects wall loss, which may lower the particle and gas levels in the sample • Long residence time allows some changes before measurement • The combustion source cannot be switched easily
Category VI–combined burning and smoke storage chamber + dilution/storage container + measuring instruments	• Stable chamber conditions allow the use of long-scan instruments • Dilution helps manage high concentrations • Ageing can be done in the storage container	• The chamber size affects wall loss, which may lower the particle and gas levels in the sample • Long residence time allows some changes before measurement • Additional containers add extra wall surfaces
Category VIIa–combustion source + smoke storage chamber + measuring instruments (connection through subsampling)	• The combustion source can be changed or adjusted • Stable chamber conditions allow the use of long-scan instruments • Ageing steps (dark or photo) can be included • Subsampling provides flexibility in how the smoke is taken	• The chamber size affects wall loss, which may lower particle and gas levels in the sample • Long residence time allows some changes before measurement • Subsampling can produce mixing differences compared to whole-flow sampling • Transfer lines may lose SVOCs if not conditioned
Category VIIb–combustion source + smoke storage chamber + measuring instruments (connection through whole-flow sampling)	• The combustion source can be changed or adjusted • Stable chamber conditions allow the use of long-scan instruments • Ageing steps (dark or photo) can be included • Whole-flow sampling gives a more representative sample	• The chamber size affects wall loss, which may lower particle and gas levels in the sample • Long residence time allows some changes before measurement • Whole-flow setups require larger and more complex plumbing • Transfer lines may lose SVOCs if not conditioned

Table 3 Summary of some key differences among the existing biomass burning smoke aerosol studies around the world

Classification basis	Categories/subtypes	Distinguishing features or modifications
General design	Category I–VIIb, each occupied with one of these	Several variations have been developed to replace the widely used fixed single-chamber type, including
	• With no combustion source (only category I)	(1) Use of dual identical smoke chambers, one as reference
	• With open burning combustion source	(2) Mobile version of chamber or whole facility
	• With closed or semi-closed burning combustion source	(3) Small-portable versions
Further modifications or improvement to general design	—	(1) Mobile or portable adaptations (2) Modular components integrated with instruments or combustion source
Smoke sampling and transfer features	—	(1) Use or absence of insulation/heating on sampling/transfer lines (2) Use or absence of particle/gas removal prior to measurement (3) Presence or absence of additional tools for SVOC re-condensation or fast chemical/physical processing
Installed smoke-characterization tools	Gas-phase and particle-phase instruments	(1) Online/real-time measuring instruments (2) Offline particle filter samplers (3) Combined setups (online + offline)
Smoke treatment during measurement	—	(1) Presence or absence of photolysis tools (2) Presence or absence of oxidant-injection ports (3) Presence or absence of T-RH controllers or adjustment tools

- Whether smoke is stored (batch system) or continuously transported (flow system).
- Whether the facility incorporates a smog chamber, oxidation flow reactor (OFR), dilution tunnel, or storage container.
- The residence-time structure imposed by the physical layout, and.
- Whether instruments access smoke *via* whole-flow or subsampling pathways.

Together, these attributes define the fundamental design class of a BB study facility and provide a hardware-based basis for comparing facilities across studies, independent of fuel type, burning conditions, or experimental protocols.

The nine categories are illustrated in Fig. 1, with additional differences in facilities included in the bottom part of the figure. The comprehensive key differences among facilities, as illustrated in Fig. 1, are then summarized in Table 3.

Meanwhile, the key advantages and limitations of each category are presented in Table 2, with a more detailed discussion of the comparisons provided in the SI, Section 5, including a conceptual table summarizing the differences in conditions represented by two main different designs: flow *versus* batch, with or without proper mixing.

As previously mentioned, Table 3 below recapitulates the key differences among facilities, as mainly shown in Fig. 1. Based on Fig. 1, some additional differences among facilities, in addition to the nine-category main differences, include the range of combustion sources used. A more detailed discussion on the combustion source, especially regarding its representability-versus-repeatability trade-off, is presented in the SI, Section 5.

4.2. 4-Letter-1-number conditioning code: purpose and limits

Table 1 summarizes the eight factors related to facility design and sampling configuration, with emphasis on the conditioning elements most relevant to OAER variability. Among them, factors 1–5 are the ones represented in the 4-Letter-1-Number (4L1N) coding system. This code provides a quick way to check basic comparability across facilities by indicating the possible influence of factors 1–5, while allowing the analysis to focus more directly on factors 6 and 7, namely, transfer-line conditioning and the facilitation of organic-gas recondensation prior to measurement, respectively. The 8th factor, mixing, is provided as an additional factor suspected as a minor influence factor.

"P" and "D" indicate photo-aged and dark-aged experiments; "C" and "O" denote chamber and oxidation-flow-reactor configurations; "M" and "S" refer to multi-stage and single-stage dilution; and "U" and "F" identify sub-sampling and whole-flow sampling systems, respectively. Additional code, which is either number "1" or number "2" refers to the presence or absence of additional early intended organic/condensable gas removal tools, respectively. The element number 6, which is the transfer line conditions, will be checked manually from the information provided in the SI, Table SI. (1), in which the comparison code of each facility is provided in the table.

It is important to note that the structural categories introduced earlier describe the facility hardware, what the system is, whereas the 4L1N code describes the operational mode used in a particular experiment, what the experiment did. Therefore, facilities belonging to the same structural category may receive very different 4L1N codes if their conditioning practices differ. The 4L1N code should be viewed as a shorthand for comparability rather than a complete description of all OA-relevant factors. In particular, two major SVOC-handling determinants, transfer-line conditioning (factor 6) and recondensation facilitation (factor 7), are not included in the code because they are either more varied in practice, *e.g.*, exact temperature used for heating, or inconsistently documented across studies. These must be extracted manually during OAER evaluation. However, for factor 7, it is likely reasonable to first assume that most facilities do not intentionally facilitate organic gas recondensation prior to measurements. Importantly, the fact that only factors 1–5 appear in the 4L1N code does not imply that these factors are more influential; their inclusion simply reflects that they are consistently reported across studies, whereas the SVOC-handling factors often play a stronger mechanistic role but cannot be codified reliably due to inconsistent documentation.

4.3 Sampling, transfer, and dilution prior to first OA measurement

Sampling, transfer, and dilution procedures play a decisive role in defining what is operationally measured as "particle mass" prior to ageing, and therefore directly influence the interpretation of organic aerosol mass enhancement ratios (OAER). The purpose of this section is not to evaluate the OAER outcomes themselves, but to clarify how the definition of "initial OA" is implicitly set by facility-specific sampling architectures.

A useful conceptual illustration is provided in an article[9] that compared four standardised particle sampling approaches originally developed for residential wood combustion emission testing as follows:

- A: Heated filter–smoke inlet → heated probe (>70 °C) → filter → "solid only".
- B: SPC-IPA–smoke inlet → heated probe → filter (solid) → impinger (condensable).
- C: Dilution Tunnel (DT)–full-flow inlet → ambient-air dilution tunnel (flow reactor-type chamber) → filter → "total particles".
- D: Dilution Chamber (DC)–partial-flow heated nozzle (90 °C) → closed batch-type dilution cabin with residence time of 0.2–2 s (35–40 °C, precisely controlled ratio 1 : 10–1 : 40) → filter → "total particles".

These approaches span solid-only particle collection using heated probes and filters (methods A and B) and dilution-based approaches that allow condensable material to repartition into the particle phase prior to collection (methods C and D).

Within the context of the present review, only the dilution-based approaches (methods C and D) are directly relevant. These methods represent whole-particle sampling strategies that include both the solid and condensable fractions in the measured particle mass. A comparison[9] demonstrates that the dilution architecture, specifically, whether dilution is applied in full-flow or partial-flow configurations, along with the associated residence time and temperature, can substantially alter the extent to which semi-volatile organic compounds (SVOCs) are retained in or excluded from the particle phase prior to measurement. This determines the presence of differences in the initial condition of the OA particle-gas partitioning and thus differences in the gained OA mass enhancement ratio (OAER). In the methods reported in the above-mentioned article,[9] either C and D or A and B, the mass quantification of the obtained particle is conducted using a filter. Among the biomass-burning ageing studies in most facilities, particle mass is most often determined using online aerosol mass spectrometers, offline filter-based analysis, or their combinations following transport through dilution stages, chambers, or flow reactors. These transport processes are similar to those experienced by particles in methods C and D of cited article,[9] which treated the initial aerosol as a whole-particle sample rather than as a fraction isolated by volatility or phase-specific conditioning.

By contrast, solid-only or split solid-condensable approaches, which are methods A and B in the referred article,[9] respectively, initially used as regulatory measurements of total particle mass freshly emitted from a compliance under test, seem irrelevant to the current review. These two alternating methods seem to exist solely to compare either compliance with the acceptable or agreed emission standard, or compliance among compliances. Therefore, these methods are primarily concerned with achieving repeatable or consistent results across repeated measurements but have no concern for preserving the full particle population for downstream processing. For this reason, these approaches are seldom used in laboratory systems that are explicitly designed to investigate organic aerosol ageing. In chamber- or OFR-based ageing experiments, even though gas-to-particle partitioning can fluctuate significantly throughout the process, the most common assumption is that particles are transferred into the ageing environment without deliberate volatility-based separation. Therefore, the aerosol entering the system represents the bulk particulate mixture at the sampling point. However, there are some facilities that intentionally installed a tool or a set of tools to extract or separate some part of the smoke, such as both the volatile organic gases and the condensable organic compounds, for the particles prior to either measurements or aging treatment. In this specific case, the insight from the stove emission measurements using methods A and B in article[7] is relevant.

To recap, within the context of the biomass burning aerosol study experiments, the article specifically mentioned and discussed in this subsection[9] is not invoked as a prescriptive methodology for ageing experiments. Instead, it serves as a conceptual reference that illustrates how choices in sampling and dilution architecture, as well as the presence of intended organic gas separation and removal, control whether condensable organic material is retained in the particle phase or lost prior to total particle mass measurement. In the ageing study, different choices can not only lead to differences in the initial particulate organic aerosol (OA) mass but also in the subsequent ageing process, resulting in differences in the organic aerosol (OA) mass enhancement ratio (OAER) and discrepancies among them. Therefore, the sampling-transfer-dilution architecture, along with any other pre-measurement or pre-ageing treatment distinction, is central to the interpretation of OAER and motivates the emphasis placed in Section. 4.4 on transfer-line conditioning and early gas-phase handling (factors 6 and 7, respectively). Some detailed examples of varying sampling and/or transfer line conditioning approaches are presented in the SI.

4.4 Proposed working hierarchy of OAER-relevant factors

Beyond the structural categories and the 4-Letter-1-Number code, several other aspects of facility design and sampling practice influence the reported OA mass enhancement ratios (OAER). As outlined in Table 1, eight conditioning-related factors appear repeatedly across the literature, although their influence is not equivalent. Based on the combined evidence from the reviewed facilities and the expected behaviour of semi-volatile materials under typical chamber and OFR conditions, a proposed working hierarchy is outlined below to help guide the interpretation of cross-facility differences.

In this framework, the first tier comprises the elements that most directly determine the availability of semi-volatile organic vapours before oxidation. These processes tend to dominate the direction and magnitude of OAER because they set the amount of condensable material entering the ageing system. This tier includes: (i) the dilution approach applied before ageing, (ii) the presence or absence of early gas-removal tools, (iii) the thermal conditioning of the transfer lines, and (iv) whether the system allowed organic vapours to recondense before reaching the instruments. Variability in these aspects can substantially alter the initial SVOC reservoir, and in turn the OA mass change that follows.

The second tier reflects differences in the chemical ageing setup, such as whether the experiments were conducted under illuminated or dark conditions and whether oxidation occurred in an OFR or smog chamber. These settings influence the oxidation pathways and ageing rates, but in many cases their effect on OAER is secondary to the SVOC-handling processes described above.

The third tier includes operational behaviours such as whether smoke was delivered through a whole-flow or a sub-sampling line and the resulting degree of mixing uniformity. These factors influence the representativeness and measurement distribution but generally contribute less to OAER variability than the first two tiers. Sampling configuration (subsampling *versus* whole-flow sampling) is placed in the third tier because although it influences the residence time, losses, and mixing during transport from the source to the ageing system, it primarily modulates the effectiveness of SVOC-handling processes rather than independently determining the available condensable vapour reservoir.

This hierarchy is not intended as a strict or universal ranking but as a practical structure for examining variability across studies. It reflects patterns observed in the reviewed literature and the expected consequences of SVOC-handling under typical laboratory conditions. Section 4 applies this proposed hierarchy when interpreting differences in OAER across the various facility types.

4.5. Integrated framework tools (9 categories + 4L1N + 3-level hierarchy) and transition to OAER evaluation

In summary, this review employs three complementary components to organise the comparison of biomass-burning laboratory studies. The nine structural categories describe the physical layout and hardware architecture of each facility. The 4-Letter-1-Number (4L1N) code captures the principal conditioning choices applied during individual experiments. Finally, the proposed hierarchy of OAER-relevant factors groups conditioning elements according to their expected influence on organic aerosol mass change.

Each component serves a distinct role. The structural categories establish the engineering context in which an experiment operates. The 4L1N code provides a consistent framework for recording conditioning settings that can be compared across studies. The proposed hierarchy identifies which of the eight facility-conditioning factors are most likely to shape OAER behaviour based on their expected effects on dilution, transfer-line handling, gas-phase removal, and ageing processes that govern the availability of condensable vapours.

Together, this integrated framework defines what each facility is, how each experiment was conducted, and which aspects of the setup are expected to exert the strongest influence on the reported OAER values. Section 4 applies this framework to evaluate how differences in conditioning choices and SVOC-handling processes contribute to the diversity of the OA mass enhancement ratios reported in the literature. Rather than adding complexity, this stepwise approach separates information extraction from interpretation by aggregating diverse experimental details into a limited set of physically motivated facility-conditioning factors, thereby allowing OAER-relevant influences to be evaluated without treating numerous poorly constrained variables as independent parameters.

A schematic illustrating the relationship among these three components as an integrated framework for cross-facility comparison is provided below (Fig. 2).

Although the framework described above is primarily intended to support qualitative interpretation, the repeated occurrence of comparable conditioning features across facilities also allows a limited semi-quantitative check to be performed. Many of the facility-design and sampling factors identified in Section. 3.3 can be expressed as categorical or ordinal variables, making it possible to examine their association with reported OA mass enhancement ratios in a consistent, though simplified, manner. This approach is reasonable in the context of a multi-facility review, where experimental conditions are diverse and formal statistical inference is not the objective. Accordingly, a semi-quantitative analysis is carried out to assess whether the direction and relative strength of the observed OAER variability are broadly consistent with the proposed hierarchy of OAER-relevant factors. The formulation of this analysis is described in Section. 2.1, while its outcomes are examined in Section. 4.

4.6. Design considerations underlying facility diversity

A comprehensive summary of the differences among existing biomass burning facilities has been introduced in the previous subsections. When developing or choosing a biomass burning facility, different concerns of the biomass burning aerosol studies could likely lead to different designs and different

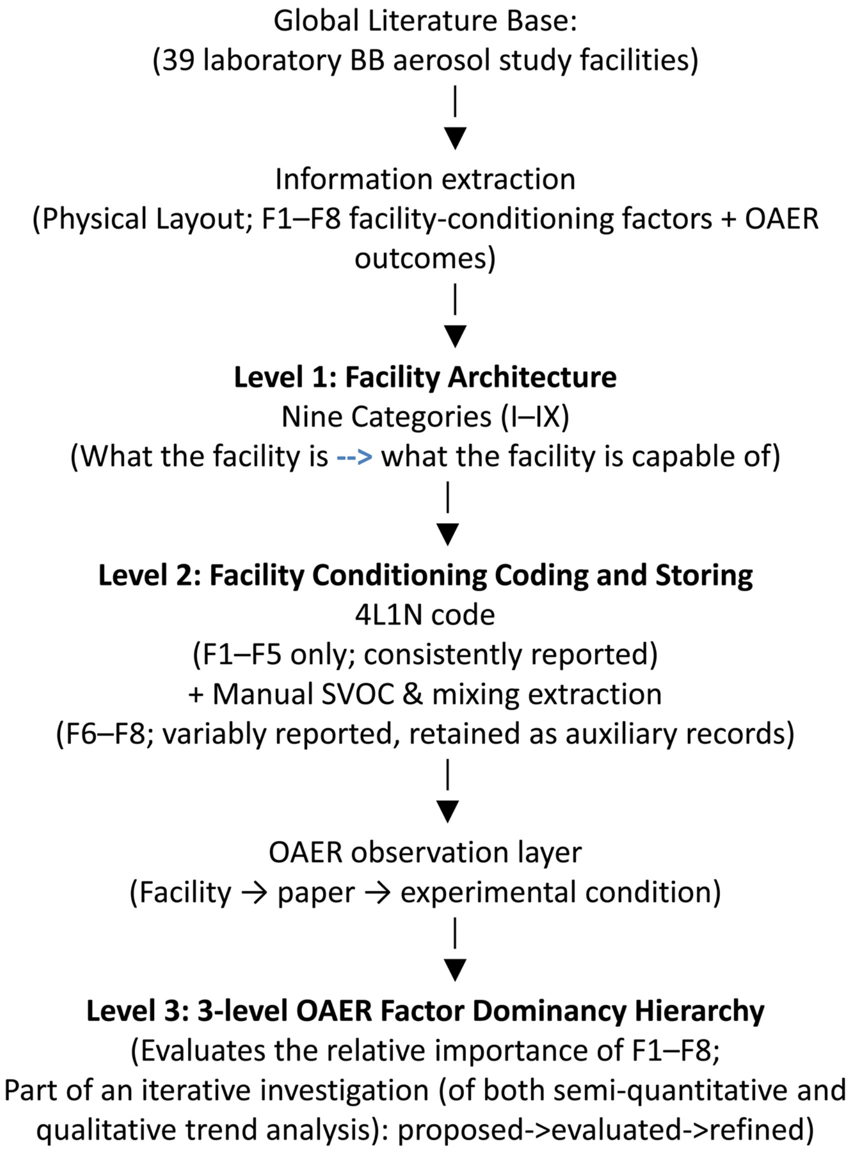

Fig. 2 Stepwise framework used in this review to organise laboratory biomass-burning aerosol studies. Levels 1 and 2 establish cross-facility comparability and reporting transparency by classifying facility architecture and encoding experimental conditioning choices (4L1N and auxiliary records). Level 3 defines a proposed interpretive hierarchy intended to evaluate the relative importance of reported conditioning factors for OA mass enhancement (OAER) once comparable information has been established, without implying formal causal inference.

features, either the main features or additional features. The concerns could be varied, mainly related to the study objectives, such as:

(1) The range of fuel type that is going to be burnt as a consideration to select a combustion source that can accommodate the fuel, *e.g.*, leaves with light weight yet high and disperse volume may be much easier to be burnt in a residential stove rather than a furnace;.

(2) The variables, *i.e.*, the experimental conditions to be explored, *e.g.*, aging *versus* none or dark aging, varying range of temperature, humidity, oxidants, and light intensity;.

(3) The smoke properties of interest, *i.e.* the range of instruments that needs to be installed, *e.g.* offline particle collectors, fast scanning instruments, or long-scan-time instruments; and.

(4) Even the specific part of the smoke, *e.g.*, gas-phase only measurements, particle-phase only measurements, or particle-phase measurements with removed semi-volatile organic compound (SVOC) fraction influence.

In addition to the study objectives, the main concerns related to the repeatability–representability trade-off or practicality and sustainability can also be key considerations for the laboratory BB study facility, as summarized in Table 4 below.

5. Discussion: facility-based interpretation of OA mass enhancement (OAER)

Given the limited number of available OA mass enhancement observations and the heterogeneous nature of laboratory

Table 4 Key considerations and their consequences in biomass burning facility design

Main concern	Details	Consequences of choices
Study objective	Range of fuel types	Selection of the combustion source
	Explored variables or experimental conditions, *e.g.*, fresh *versus* aged measurements	Added installed tools or equipment, *e.g.*, T-RH adjustment, presence/absence of dark-(additional oxidant(s) injection)-aging and/or photoaging tools
	Smoke properties of interest	Selection between batch-type or flowing-type reactor that is suitable for the installation of long-scan-time measuring instruments and fast measuring instruments, respectively
	Whole or a specific part of the smoke	Presence or absence of smoke gas phase removal or separator
Repeatability–representability trade-off	Building a facility that produces highly repeatable, controlled, and comparable data *versus* one that produces realistically variable, field-representative data Whether or not taking into account the influence or contribution of ambient air and/or other source-type pollutants	Selection of the combustion source, including alternative choice to construct a design that samples smoke directly from BB smoke-rich ambient air (no self-generated combustion source)
Practicality and sustainability	Whether the facility can actually be built, maintained, and evolved (implementation feasibility)	Selection of the whole design. For example (1). One joined combustion and smoke storage system *versus* two separated systems, so that the combustion source can be easily changed between different types of combustion sources (easily connected and disconnected) (2). Alternative choice to make the whole design mobile rather than fixed or static

systems, qualitative synthesis forms the primary basis of interpretation in this review. A semi-quantitative analysis is subsequently applied as a supplementary consistency check to examine whether qualitatively inferred factor importance is broadly reflected in the compiled dataset, rather than to establish formal statistical relationships. Details of the data processing, including the selection of OAER observations, are provided in the SI (Section 4.b(ii)), "The Full Master Dataset: 42 observation points extracted from Table S1 and their transformation into four datasets." As a reminder, this review is designed to capture the full architectural diversity of existing biomass-burning facilities, not solely those explicitly used for aerosol ageing studies. Consequently, although 39 facilities are identified and classified, only 11 facilities report sufficient OA mass enhancement information to be examined further for OAER outcomes. Within this subset, most facilities fall into Categories IVa and b and VIIa and b, with Category I appearing less frequently.

Prior to further detailed discussion of each tested factor in influencing the OAER outcome, it is likely useful to briefly clarify terminology related to the volatility of organic aerosol constituents. Organic compounds are commonly classified according to their effective saturation concentration (C*), following the volatility basis set framework.[82,85] In this approach, organic species are broadly grouped as volatile organic compounds (VOCs), intermediate-volatility organic compounds (IVOCs), and semi-volatile organic compounds (SVOCs). For typical atmospheric organic aerosol (OA) mass concentrations in the order of 0.1–100 μg m^{-3}, compounds with effective saturation concentrations of approximately 0.3–300 μg m^{-3} are generally considered SVOCs, while those with C* values between roughly 300 and 3×10^6 μg m^{-3} fall into the IVOC range.[85] IVOCs reside primarily in the gas phase but can contribute substantially to secondary organic aerosol (SOA) formation following oxidation. VOCs represent the most volatile fraction, and also serve as important SOA precursors through gas-phase oxidation pathways. At the lowest end of the volatility spectrum, low-volatility (LVOC) and extremely low-volatility organic compounds (ELVOC) are largely confined to the particle phase and contribute efficiently to particle growth.[85]

5.1 Qualitative interpretation of OAER variability across facilities

5.1.1 Facilities with early organic-gas removal or dark aging without added oxidants (short, near-deterministic). Based on Table SI. 1 and SI. 2, removing the gas phase of the smoke, especially the organic gases, VOC and SVOC gases, can hardly lead to OA mass enhancement. This happened in chamber facility number 25, P.C.S.F.1, with both high-temperature heated line and gas phase removal applied. It could increase the mass slightly due to functionalization of the particle phase, but only at the beginning, which, upon further aging, specifically photoaging, fragmentation and thus evaporation, an OA mass decrease could likely happen, resulting in a net negative OA mass change, *i.e.* less than one OAER. This shows that the gas phase smoke, especially the organic compounds, is essential in SOA formation or OA mass enhancement.

Alternatively, without added or injected oxidants, chamber dark aging treatment in a subsampling system using a multistage dilution, facility number 29, D.C.M.U.2, neither resulted in SOA formation nor decreased the OA mass, despite the absence of pre-treatment applied to remove the gas-phase smoke before aging. In the absence of a sufficient oxidizing agent in the treatment without early-stage gas removal, particles can only experience gas-to-particle partitioning during dark aging conditions, normally leading to only a small change or just a net zero change.

5.1.2 Facilities without early organic-gas removal (main qualitative synthesis + SVOC-handling approaches). In the experiments with code number 2 and "P" representing "photoaging" as the first letter in the code, the observed OA net mass evolution can vary from an increase, decrease, or stagnant, likely affected more by the variation in the conditionings applied to the transfer line and thus the organic compound gas-to-particle partitioning, which is not included in the comparison codes.

Most facilities applied treatment that prevented condensation of the organic gases on the sampling or transfer tube line. This was done through either heating or insulating the line. Some facilities simply insulated the sampling and transfer lines without using heat to maintain a relatively constant exhaust temperature. This method helped prevent condensation from cooling while ensuring that some particles did not evaporate and disappear. Conversely, other facilities use either both insulation and heating or just heating to prevent the condensation of organic gases, particularly on the sampling or transfer tube lines. However, this approach of including transfer line heating leads to another concern that should be noted while trying to interpret the measurement results, as discussed below.

When applying heat to the sampling or transfer line to prevent the condensation of the organic gases on the tube lines, the SVOC fraction of the particles could evaporate and turn into the gas phase. Too high temperatures could also evaporate the whole part of the particle(s), reducing the particle number concentration in the sample stream.

Following this condition, some facilities chose to facilitate the re-condensation of the SVOC fraction in the gas phase back into the particle phase before the measurements or aging treatment. Similarly, some facilities did facilitate any quick chemical or physical processing before measurements. For example, some facilities provided either a mixing with dry air or an intentionally designed short residence time sufficient for the quick chemical or physical processing before measurements. Those were done regardless of the use of heat in the sampling and transfer line. These facilities assumed or expected the likely presence of some quick, either chemical or physical processing that was unavoidable and better facilitated before measurements or before aging treatment in the chamber, so that each experiment has relatively more stable and uniform initial conditions, leading to reliably more comparable results to each other. However, some other facilities with the opposite point of view prevented any reaction or physical processing from happening before the start of either the aging treatment or first measurement, or both.

In summary, without the intention of organic gas removal through the installation of the corresponding additional tool(s), laboratory facilities employ at least three distinct approaches for handling SVOC and condensable organic compounds before measurement or aging:

(1) SVOC gas preservation: keep SVOCs in the gas phase while preventing wall condensation, typically by applying elevated temperatures and/or insulation. There are two more different conditions in this part.

(1 a) Gas-phase preservation to prevent condensation of freshly emitted gas only: insulation or line heating at sufficiently moderate temperature.

(1 b) Active particle-evaporation during transfer, *i.e.*, intentional volatilization of some or whole fraction of the particles' organic compounds: typically, high-temperature transfer line heating.

(2) SVOC recondensation facilitation: allow SVOCs to remain in the gas phase during transfer, but facilitate recondensation just before measurement (*e.g.*, *via* dilution and/or mixing or controlled cooling), typically applying elevated temperatures and/or insulation too.

(3) SVOC particle retention: avoid heating altogether to preserve SVOCs in the particle phase throughout the sampling and transfer process, typically not applying any heating or insulation to the sampling and/or transfer lines.

The above-mentioned three different purposes will affect the initial condition of gas-to-particle partitioning, and then further affect the observed changes in the particles relative to their initial condition. Assuming that all other conditions, setups, or designs were the same, with the exact sample and burning conditions and thus a relatively similar freshly emitted organic gas phase, the 1st approach will likely lead to a condensation-driven increase in the organic particle mass, while the 2nd and 3rd approaches likely have either a constant or decreased organic particle mass.

Example(s) of the 1st approach were in facility number 21, P.C.M.U.2,[37] while example(s) of the 2nd and 3rd approaches were in facility number 30.b., P.O.M.U.2,[51] and facility number 30.a., P.O.S.U.2,[1] respectively.

Then, based on the discussion above, it can be similarly inferred that the initial measurement time, regarding the initial conditions under which the first measurement was made and recorded to be later compared with the final or the end-of-experiment measurement, can be an important factor affecting the discrepancies in the reported laboratory study results, either from the same or different facilities. This is in addition to line loss and dilution factors, which will also certainly affect the discrepancies in similar explanations.

Deviations from the expected OAER trends within each approach, as presented in Table S1 and S2, can arise primarily from variations in oxidant availability, residence time, and oxidation extent. In approaches where SVOCs are volatilized prior to aging, insufficient oxidant exposure or the preservation of elevated temperatures or short residence times may favour thermodynamic evaporation over secondary formation, leading to stagnant or decreasing OA mass. Conversely, under sufficiently high oxidant levels and longer residence times, continued SOA formation can dominate, yielding net OA

Table 5 Coefficients of the semi-quantitative OAER factor analysis with all factors included in the test. Bold indicates the three dominant factors, reflected by their factor dominance (D) value

	First dataset				Second dataset			
	All fuels (A1); [$N = 40$; $R^2 = 0.514$]		Wood only (A2) [$N = 40$; $R^2 = 0.561$]		All fuels (A3) [$N = 25$; $R^2 = 0.7104$]		Wood only (A4) [$N = 21$; $R^2 = 0.722$]	
Factor	β‖D	exp(β)	β‖D	exp(β)	β‖D	exp(β)	β‖D	exp(β)
Intercept	0.278	1.320	0.125	1.133	0.125	1.133	0.175	1.19
F1: Aging mode (photo = 1)	−0.078‖0.078	0.925	−0.033‖0.033	0.968	0.021‖0.021	1.022	0.000‖0.000	1.000
F2: Oxidant system (OFR = 1)	0.327‖**0.327**	1.387	0.536‖**0.536**	1.709	0.347‖0.347	1.414	0.391‖0.391	1.478
F3: Dilution architecture (multi-stage = 1)	0.258‖0.258	1.294	0.091‖0.091	1.096	0.240‖0.240	1.271	0.187‖0.187	1.206
F4: Sampling configuration (sub-sampling = 1)	0.258‖0.258	1.294	0.091‖0.091	1.096	0.240‖0.240	1.271	0.187‖0.187	1.206
F5: Early gas-phase removal (presence = 1)	−0.361‖**0.361**	0.697	−0.716‖**0.716**	0.489	−0.446‖**0.446**	0.640	−0.541‖**0.541**	0.582
F6: Transfer line conditioning	0.054‖0.162	1.055	0.208‖**0.624**	1.231	0.100‖0.100	1.105	0.122‖0.122	1.130
F7: Facilitated recondensation	0.192‖0.192	1.212	0.169‖0.169	1.184	0.142‖**0.426**	1.153	0.153‖**0.459**	1.165
F8: Mixing quality	−0.793‖**0.793**	0.452	−0.308‖0.308	0.735	−0.605‖**0.605**	0.546	−0.549‖**0.549**	0.577

increases even within approaches that initially suppress particle-phase organics.

When different temperatures are applied, there are two more different scenarios that can occur in the above-mentioned first approach. However, there are no universal temperature cut-offs to determine which temperature "only preserves gas" *versus* which temperature causes particle evaporation. It depends on the compound volatility (C*),[51,52,84] the total bulk organic aerosol mass concentration in the air,[52,53] the residence time,[54] and the enthalpy of vaporization of the species.[55] Using 40 °C heating,[15,16] organic gases seemed available enough during measurement, so that the enhancement ratio depends on both the available oxidant level and residence time.

Lastly, by comparing the 1st approach in the current subsection with the modified version of it in the previous subsection, *i.e.*, the applied early organic gas phase removal, it can be generally highlighted that the presence of the organic gas at the start of the aging or first measurement time is the most crucial aspect for SOA formation. Additionally, even under identical combustion conditions, differing thermal and dilution protocols can significantly shift the balance between functionalization and fragmentation, ultimately shaping the observed OA mass trends.

5.2 Semi-quantitative assessment of OAER dependence on facility features (supporting assessment)

The following semi-quantitative analysis does not redefine the proposed hierarchy. Instead, it provides a structured assessment of how strongly individual facility-conditioning factors influence the observed OAER within that conceptual framework. The hierarchy itself is intended as a physically motivated organizing tool that distinguishes when and how different factors act during aerosol processing, whereas the semi-quantitative results evaluate the relative strength of these influences without altering the tier structure. Additionally, a structured check of whether directional trends are consistent across a diverse set of laboratory studies was expected in this analysis, whereas statistically rigorous relationships were not. For these reasons, the coefficients obtained from the analysis are thus interpreted in terms of relative influence and trend direction rather than as precise quantitative estimates. The results of the regression analysis are presented in Tables 5 and 6

In the proposed hierarchy, the factors in the 1st tier are those applied prior to the start of the initial time of aging or measurement, which include dilution, presence or absence of early gas-removal tools, thermal conditioning of the transfer lines, and presence or absence of facilitated re-condensation of the organic gas prior to a measurement time point marked as the initial or baseline condition. Based on Table 5, the three most dominant factors in the main dataset and the three subsets of it frequently scatter around the above-mentioned factors, particularly factors F5–F7. The early gas-phase removal factor (F5) is the most consistent, appearing among the three most dominant factors in all four datasets and showing a strong suppressive effect, as expected. Transfer line conditioning (F6) and facilitated early recondensation (F7) accounted for 25% of the 12 positions of the three highest OAER-influencing factors across the four datasets.

A factor competing with factors F6 and F7 comes from the different types positioned in the different tiers, *i.e.*, lower tier (tier 2) in the proposed hierarchy, which was the oxidant system, chamber *versus* OFR (F2). It appears twice in the three highest dominant factors, yet always in the lowest position between the other two. These results for F2 likely suggest that this factor is a competing factor but only under occasional conditions. As briefly mentioned, any one of the oxidation condition-related factors is generally thought of as roughly similar or uniform across the different studies generated under typical laboratory conditions. This is especially within the same type of factor, *e.g.*, across chamber-photoaging studies, but can also apply across different types as they tried to mimic the

Table 6 Coefficients of the semi-quantitative OAER factor analysis with F7 and F8 excluded in the test. Bold indicates the three dominant factors, reflected by their factor dominance (D) value

	First dataset						Second dataset	
	All fuels (B1) [$N = 40$; $R^2 = 0.352$]		Wood only (B2) [$N = 25$; $R^2 = 0.420$]		All fuels (B3) [$N = 25$; $R^2 = 0.450$]		Wood only (B4) [$N = 21$; $R^2 = 0.500$]	
Factor	β||D	exp(β)	β||D	exp(β)	β	exp(β)	β	exp(β)
Intercept	0.302	1.353	0.140	0.151	0.130	1.139	0.160	1.174
F1: Aging mode (photo = 1)	−0.052||0.052	0.949	−0.020||0.020	0.980	0.040||0.040	1.041	0.020||0.020	1.020
F2: Oxidant system (OFR = 1)	0.180||0.180	1.197	0.420||**0.420**	1.522	0.270||0.270	1.310	0.300||**0.300**	1.350
F3: Dilution architecture (multi-stage = 1)	0.402||**0.402**	1.495	0.150||0.150	1.162	0.300||**0.300**	1.350	0.220||0.220	1.246
F4: Sampling configuration (sub-sampling = 1)	0.378||**0.378**	1.459	0.140||0.140	1.150	0.300||**0.300**	1.350	0.220||0.220	1.246
F5: Early gas-phase removal (presence = 1)	−0.312||**0.312**	0.732	−0.720||**0.720**	0.487	−0.440||**0.440**	0.644	−0.550|**0.550**	0.577
F6: Transfer line conditioning	0.072||0.216	1.075	0.220||**0.660**	1.246	0.100||**0.300**	1.105	0.120||**0.360**	1.128

common atmospheric conditions. However, more extreme aging conditions could still possibly be applied in any study for faster and more noticeable effect as the reasons, for example. This case certainly needs to be reported and given more attention when evaluating the dominance across tested factors such as in the current review study. The current study did not compare details of the aging conditions. However, in general, these factors were kept in the lower positions in influencing OAER outcomes compared to the early smoke handling and conditioning-related factors. The aging mode (photoaging *versus* dark aging with added/injected oxidants) was consistently the lowest-influencing factor among the eight factors across all four datasets in Table 5.

Alternatively, the mixing factor (F8), which was initially considered the weakest factor in the proposed hierarchy, ranks among the three dominant factors as many as three times across the four datasets in Table 5, with strong negative effects competing with early gas phase removal (F5). This negative correlation between OAER and mixing was unexpected when synthesizing the current eight facility-related factors. Mixing can either enhance or suppress SOA formation depending on its timing and coupling with dilution and residence time: mixing during ageing promotes vapour–particle equilibration and oxidant homogeneity, whereas early pre-measurement mixing can increase the baseline OA *via* re-condensation and reduce the apparent SOA enhancement ratios. However, the term mixing as the tested influencing factor in the current review study refers to that applied just during aging, whereas mixing applied prior to the first initial condition measurement implicitly falls within the early facilitated recondensation factor.

Other negative effects of mixing can possibly arise from an exceptional case of aggressive mixing, which increases particle and vapour wall loss, reducing the effective SOA yield. While particle wall-loss corrections can partially account for deposited particulate mass, they do not recover oxidized vapours that are lost to walls or advected out of the system before condensation; therefore, mixing-induced reductions in effective SOA formation cannot be fully resolved by standard wall-loss correction approaches. Another possible cause is the use of mixing in a flowing system such as OFR. Unlike in the chamber system, the effect of mixing is not well distributed and can reduce the local residence time near particles, promoting the oxidized vapours, which can probably improve due to the mixing-driven better oxidation, to exit before condensing.

However, in the current study, the negative impact of mixing could be caused, contributed to, or resulted from the still-limited and poor reporting and storage of mixing-related information in the referred articles. It can also be worsened if formal definitions of mixing in the current context of the newly developed investigation study are not sufficiently available to determine the presence or absence of mixing based on the information in the reviewed articles. In the current study, the cause was likely the former, *i.e.*, the less explicit reporting of mixing in the reviewed articles. In the current study, almost all observation points had F8 = 0 (Section 4 in SI), while most of the reviewed studies were distributed among those that favoured SOA formation. This is certainly the reason for the negative correlation between mixing and OAER outcomes. There was one observation point that had an F8 = 1 value, but it unfortunately seems to even worse it because experiment F8 = 1 belongs to a specific or context-based dark aging experiment at UoM, where no additional oxidants were applied, leading to a stagnant instead of increased OAER (as a note, in future studies, dark aging should be more carefully evaluated as distinguished between that which is truly dark-aging, *i.e.* applying added required oxidants, and that acting just as background experiments). In the current study, if the F8 = 1 values are applied by, for example, assuming that all chamber experiments used mixing in their system whether it was mentioned it in the articles or not, the mixing factor coefficients become positive (Section 4 in SI).

Facilitated re-condensation (F7) was initially considered as a potential factor influencing OAER, motivated by the hypothesis that intentional vapour–particle re-equilibration prior to baseline OA determination could increase the initial particle-

Table 7 Summary of the current semi-quantitative analysis (SQA) direction results and both/either the suspected and/or proven dependencies, including inter-factor (F1–F8) dependencies

Factor group	Factor	Expected direction for higher OAER	SQA observed OAER increasing factor	Key notes/dependencies
Relatively isolated factors	Oxidant exposure (photo-aging *vs.* dark aging)	Photo-aging	Minor and no consistent direction	—
	Aging system (chamber *vs.* OFR)	Chamber	OFR	Stronger and/or more effective (yet not excessive) oxidation of the OFR system in the current dataset
	Dilution architecture (multi-stage *vs.* single-stage)	Multi-stage dilution	Multi-stage dilution	Consistent with improved SVOC preservation of multi-stage dilution High organic gas availability upon evaporation caused by the abrupt dilution in the single-stage dilution likely to be countered by following loss of the gas/vapor
	Early facilitated re-condensation (absent *vs.* present)	Absence	Presence (ambiguous)	Likely reflects reporting or coding ambiguity rather than true physical effect
Less isolated factors	Sampling configuration (whole-flow *vs.* subsampling)	Whole-flow sampling	Subsampling	Strongly dependent on SVOC preservation quality of subsampling system
	Early gas-phase removal (absent *vs.* present)	Absence	Absence	All removals in the current dataset coupled with high-T Regarding possible re-equilibration driven evaporation of the SVOC fraction in the particles prior to first measurement or aging time, effect can depend on • The heating presence/absence and the used temperature (F6) • Relative position in the sequence of the pre-aging processing or treatment, as well as its resulting early residence time
	Mixing (absent *vs.* present)	Presence	Absence	Likely reflects reporting or coding ambiguity rather than true physical effect Likely system-dependent: Beneficial in chambers, suppressive in OFR (F2); thus, can be affected by the data structure or distribution Excessive mixing may enhance vapor wall loss
Least isolated factor	Transfer-line heating	High temperature	High temperature	Strong coupling with gas-phase removal (F5) and early re-condensation (F7) timing; thus, can be affected by the data structure or distribution

phase OA mass and thereby reduce OAER. In this conceptual model, F7 would be expected to act as a suppressive factor. However, when included in the regression analysis, as shown in Table 5, F7 appears as a moderate positive contributor to OAER. This behaviour is inconsistent with the original physical hypothesis and instead indicates that F7 acts as a proxy for well-controlled experimental setups that also favour efficient SOA formation during aging. Consequently, its apparent dominance reflects correlated facility characteristics rather than a clearly defined physical process operating prior to baseline OA determination.

As summarised in Table SI.4, the majority of studies do not explicitly describe any intentional experimental step designed to promote re-condensation or vapour–particle re-equilibration prior to baseline OA measurement. In several cases, terms such as "stabilization" and "baseline defined after stabilization" are used; however, these descriptions refer to routine chamber equilibration or instrument stabilisation procedures rather than a deliberate physical mechanism intended to enhance re-condensation of semi-volatile organic compounds (SVOCs), respectively. Importantly, no study explicitly states that this stabilization was implemented with the aim of increasing the initial particle-phase OA mass.

Moreover, vapour–particle re-equilibration naturally occurs as a consequence of cooling, dilution, and residence time within most experimental systems. As a result, explicit reporting of re-condensation-related procedures does not necessarily imply a stronger or more effective re-condensation process than in facilities where these processes occur implicitly. In practice, any OAER-lowering influence of deliberate pre-equilibration through increased baseline particle-phase OA and reduced gas-phase SVOC availability for subsequent ageing may be counterbalanced by other operational factors with opposing effects. These include dilution strategy, sampling configuration, and transfer-line conditioning, which can preserve organic vapours and maintain their availability for oxidation, yielding comparable or even higher observed OA mass enhancement ratios.

Given the lack of explicit, consistent documentation and the high potential for proxy effects, facilitated re-condensation does not meet the evidentiary threshold required for treatment as an independent variable in the semi-quantitative regression. Therefore, factor F7 was next excluded in the repeated multi-linear regression analysis, as shown in Table 6, to avoid misattribution and double counting of effects. Processes related to vapour equilibration are instead implicitly represented within broader aerosol handling and conditioning factors, including dilution architecture, sampling configuration, and transfer-line conditioning. Additionally, due to a similar reason, the mixing (F8) factor was also excluded.

Removal of the two ambiguous factors (Table 6) reconfirmed the strong suppressive effect of early gas removal and the lowest effect of different oxidation approaches, *i.e.*, photoaging or dark aging (with added oxidant). The oxidant system, whether aging is conducted in a chamber or an OFR system, has considerable competing effects in magnitude with the high or moderate (not the dominant) smoke-handling and conditioning factors, in which OFR favours SOA formation more than chambers. This higher positive effect of OFR over chambers is expected, as OFR can generally introduce stronger or more effective oxidation, benefiting SOA formation, unless excessive oxidation-driven fragmentation occurs. The transfer line conditioning factor consistently contributes to increased OAER at both moderate and high magnitudes. However, it is important to note that transfer line heating conditions can be coupled strongly with other factors, such as early-stage gas phase removal. Therefore, the effect of this factor can also be influenced by the data structure or distribution. Lastly, it is possibly useful to notice that after removing the two factors, the R^2 values decrease in any dataset. Therefore, once more consistent or proven data input of mixing and early facilitated recondensation is available, and the full F1–F8 model should be used instead of the reduced model, *i.e.* F1–F6.

The dilution architecture (single-step *versus* multi-stage) can influence reported OAER through several competing processes that act prior to ageing and therefore shape the initial OA baseline. An abrupt, single-step dilution reduces the OA loading and drives rapid SVOC evaporation *via* gas–particle repartitioning, decreasing the particle-phase OA mass and altering the available SVOC reservoir.[25,26] Field observations indicate that such dilution-driven evaporation of POA can, under certain conditions, lead to a near net enhancement of total OA mass when the evaporated POA is subsequently oxidized and forms a dominant fraction of SOA, provided that the initial POA mass is quantified prior to evaporation and chamber wall-loss effects are not aplicable.[24] In chamber studies, by contrast, this early evaporation can either (i) increase OAER mathematically by lowering the initial OA denominator or (ii) suppress subsequent OA formation if evaporated SVOCs and reactive precursors are lost to walls, vents, or sampling lines before they can re-partition or oxidize.[25,26] Multi-stage dilution distributes dilution more gradually and can in some cases better preserve the coupled gas- and particle-phase material prior to ageing,[25,26] although additional flow-path complexity may increase line losses unless transfer-line conditioning is effective. The coupling between dilution pathway and transfer-line conditioning is evident in facility descriptions employing sequential dilution and heated stainless-steel transfer lines designed to limit SVOC losses.[38] Consequently, the direction of the single- *versus* multi-stage dilution effect on OAER is expected to vary across studies depending on the volatility distribution, baseline definition, and conservation of organic vapours and particles during transfer.[25–27]

Similarly, the sampling configuration (subsampling *versus* whole-flow transfer) affects OAER through competing influences on the residence time, dilution history, and losses prior to ageing. Subsampling configurations typically deliver only a fraction of the diluted exhaust stream to the ageing system, which can reduce the vapor and particle loading and amplify dilution-driven repartitioning effects.[25,26] In contrast, whole-flow transfer may reduce particle losses but can increase vapor exposure to tubing surfaces, enhancing gas-phase adsorption if the lines are unheated or poorly conditioned. These contrasts are apparent in facility descriptions comparing subsampling systems with heated transfer lines to whole-flow sampling configurations emphasizing particle conservation despite potential vapor losses.[38] Because OAER is defined relative to an initial OA baseline, different balances among early SVOC evaporation, vapor retention or loss, and delivered OA mass can yield higher or lower OAER depending on the net outcome.[25–27] Accordingly, any directional association observed within a compiled dataset should be interpreted as contingent on co-varying design choices rather than as a universal causal relationship.

Because these design choices are frequently coupled, directional associations inferred from limited sample counts should be regarded as indicative rather than definitive, underscoring the need for harmonized reporting to enable conditional comparisons in which individual factors can be evaluated within subsets of studies sharing comparable facility-conditioning characteristics (*e.g.*, similar transfer-line treatment and ageing approach). Table 7 provides a summary of the main points discussed in this semi-quantitative analysis subsection.

Limitations. (1) Fuel type and burning phase were recorded but not controlled across studies. (2) Environmental conditions (T, RH, chamber S/V, and wall loss rates) were not uniformly reported and thus not included in the coding. (3) Some TF/line-conditioning metadata were incomplete for a few facilities. These constraints make this study an exploratory assessment of whether facility-design signals are detectable above the background of combustion variability; thus, follow-up, harmonized inter-facility benchmarking (identical fuels and synchronized oxidant exposure) is recommended to quantify the relative contributions.

6. Conclusion

This review synthesizes laboratory approaches for simulating and characterizing biomass-burning aerosol emissions by organizing 39 facilities into a nine-category structural taxonomy. Supplemented with a reporting framework of eight facility-conditioning factors, partly encoded using the 4-Letter-1-Number (4L1N) scheme, this structure enables a consistent cross-study comparison of organic aerosol aging. The semi-quantitative analysis shows that the factors defining the initial smoke state, including dilution strategy, sampling configuration, transfer-line conditioning, and early gas removal, exert a greater influence on the OAER outcomes than the specific oxidation environment. This hierarchy explains why ostensibly similar experiments often report divergent OAER values and underscores the importance of transparent reporting of smoke-handling practices. Although combustion variability remains an irreducible source of scatter, consistent documentation of SVOC handling, mixing, and recondensation pathways will strengthen cross-facility synthesis. The design principles distilled here extend beyond OAER, offering a basis for interpreting other aerosol properties and advancing reproducible laboratory simulations of biomass-burning emissions.

7. Future directions and research needs

This review highlights that the discrepancies across biomass-burning laboratory studies arise primarily from how semi-volatile organic vapours (SVOCs) are managed before and during ageing. Therefore, strengthening reproducibility and comparability requires clearer control, documentation, and decoupling of SVOC-related processes. Key directions include:

(i) SVOC handling protocols: establish harmonised guidelines for early gas removal, transfer-line conditioning, dilution architecture, and sampling configuration. These factors dominate OAER variability and must be reported consistently to reduce bias.

(ii) Recondensation pathways: conduct targeted experiments that intentionally promote vapour–particle re-equilibration, with residence times and baseline OA documented before and after conditioning. This will isolate recondensation from general handling.

(iii) Mixing effects and coding: mixing, once considered minor, shows high dominance in OAER outcomes. Future studies should quantify mixing efficiency with tracer diagnostics and ensure consistent coding/reporting to avoid misclassification.

(iv) OFR *vs.* chamber choice: while secondary to SVOC handling, the choice of ageing system competes as a moderate to high factor. Comparative studies should document oxidation environment details and test how OFR *vs.* chamber setups interact with SVOC conditioning.

(v) Photoaging *vs.* dark aging: current data show only minor, non-systematic influence, likely reflecting relatively standard oxidation conditions. Nonetheless, detailed reporting remains essential to prevent misinterpretation under extreme oxidant exposure or dark ageing with no oxidant.

(vi) Inter-facility benchmarking: coordinated campaigns burning identical fuels under harmonised oxidation conditions, while deliberately varying SVOC-management steps, can reveal systematic deviations and define correction factors.

(vii) Broader emission scenarios: expand facility designs to tropical fuels, peat fires, and mixed-phase combustion to capture global variability.

(viii) Data harmonisation: develop open-access repositories documenting facility architecture, conditioning choices, and OA evolution metrics. Once SVOC processes are consistently reported, contextual factors such as chamber S/V ratio, wall-loss rates, and environmental controls can be incorporated as quantitative covariates.

Establishing these advancements would enable laboratory studies to serve not only as controlled analogues but as reliable quantitative bridges to field observations, ultimately improving their impact on atmospheric modelling and policy frameworks.

Author contributions

S. A. S. conceived the study, designed the analytical framework, collected and curated all literature, performed the qualitative and semi-quantitative analyses, and then wrote both the original and revised draft of the manuscript. S. A. S. also led the methodological refinement and iterative development of the facility-comparison framework and dominance hierarchy. M. D. E. assisted with updating the literature database to include recent (2024–2025) publications, participated in early

discussions on the range of physical layouts of laboratory facilities, and provided feedback on literature selection. M. D. E. also offered comments on the presentation of the semi-quantitative approach and the overall structure and clarity of the manuscript. M. S. R. contributed to manuscript review and provided editorial feedback and language refinement, leveraging his background in atmospheric physics to improve clarity and technical expression.

Conflicts of interest

No conflict interest in this paper.

Note added after first publication

This article replaces the version published on 20 Jan 2026, which contained errors in Fig. 2.

Data availability

Initially, no original data was used in this current study. The data were taken directly from the literature, as summarized in Table provided in supplementary information (SI). Following a reviewer suggestion, a simple semi-quantitative analysis was added, leading to the generation of new datasets in which the derived data are expressed as coded factors and provided in the supplementary information. Ref. 28–36, 39–50, 56–81, 83, 86–103 are cited in the SI. Supplementary information is available. See DOI: https://doi.org/10.1039/d5ea00146c.

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