THESIS

EVALUATING SOURCES OF VOLATILE ORGANIC COMPOUNDS IN COLORADO WORKPLACES VIA POSITIVE MATRIX FACTORIZATION

Submitted by

Jadelyn Lippmann

Department of Civil and Environmental Engineering

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Master's Committee:

Advisor: Ellison Carter
Co-Advisor: none

Melissa Burt
Rebecca Atadero

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ABSTRACT

EVALUATING SOURCES OF VOLATILE ORGANIC COMPOUNDS IN COLORADO WORKPLACES VIA POSITIVE MATRIX FACTORIZATION

Recognition of the health risks associated with exposure to volatile organic compounds (VOCs), particularly in indoor environments, has increased the need for a stronger understanding and management of air quality. Exposure to VOCs, emitted from sources like building materials, office equipment, and consumer products, have been linked to both acute and chronic health outcomes, including respiratory issues and carcinogenic effects. While research on residential indoor air quality is extensive, fewer studies have characterized VOC exposure, particularly in workplaces, where people may spend a significant portion of their time. Work presented in this thesis addresses this knowledge gap through analysis of a comprehensive empirical study of VOC concentrations in 50 diverse workplaces across the State of Colorado.

This study, is part of a broader initiative led by Colorado State University in partnership with the Colorado Department of Public Health and Environment (CDPHE), utilized weeklong air sampling with SUMMA canisters and analyzed 61 target VOCs via EPA Method TO-15. Positive Matrix Factorization (PMF) modeling was employed to identify and apportion the sources of VOCs, providing insights into the relative contributions of indoor and outdoor pollutants. The findings inform understanding of VOCs measured in workplaces, and the design and implementation of targeted interventions to improve indoor air quality in occupational settings, particularly in underserved communities. This work contributes to advancing exposure science and supports healthier, and more sustainable indoor environments where people work.

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1. INTRODUCTION

Increasingly, the need to understand exposure to volatile organic compounds (VOCs) is gaining traction as research is pointing towards their potential for chronic and acute health outcomes. VOCs range widely – from benign to hazardous – in their association with adverse human health effects. Many VOC species are not associated with adverse effects on human health; however, numerous other VOCs (e.g., benzene) have been classified as mutagenic or carcinogenic. [1] One of the most comprehensive and first evaluations of the prevalence and patterns of VOCs in indoor environments was undertaken at the end of the 20th century by the United States Environmental Protection Agency (EPA) Total Exposure Assessment Methodology (TEAM). Their analysis of hundreds of VOC samples across hundreds of U.S. residential homes showed that about a dozen common organic pollutants, including known human carcinogens, were consistently measured at levels that were two to five times higher inside homes compared to measurements of those same VOCs outdoors, regardless of whether the homes were located in rural or highly industrial areas.[2] During and for several hours immediately after certain activities, such as paint stripping, indoor levels of VOCs associated with these activities may be 1,000 times background outdoor levels.[3] While people use products containing VOCs, they can expose themselves and others to high pollutant levels. Further, elevated VOC concentrations can persist in the air long after the initial activity.[4]

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[1] Y. Xiong, K. Du, and Y. Huang, “One-third of global population at cancer risk due to elevated volatile organic compounds levels,” *npj Climate and Atmospheric Science*, vol. 7, no. 1, pp. 1–11, Mar. 2024

[2] United States Environmental Protection Agency, “Volatile Organic Compounds’ Impact on Indoor Air Quality | US EPA,” *US EPA*, 2018.

[3] United States Environmental Protection Agency, “Volatile Organic Compounds’ Impact on Indoor Air Quality | US EPA,” *US EPA*, 2018.

[4] US EPA, “What are volatile organic compounds (VOCs)?,” *US EPA*, Feb. 19, 2019.

VOCs are frequently measured at considerably higher concentrations indoors compared to ambient outdoor environments and pose a potential risk to health, given the amount of time humans spend indoors, thus elevating their inhalation exposure to the VOCs found there. VOCs measured indoors may originate from various sources within the building, with common sources being building materials (e.g. insulation, paint, staining products), combustion processes (e.g. smoking, cooking, home heating systems), consumer (e.g. cleaners, air fresheners, candles), and personal care products (e.g. hair spray, fragrances). VOCs measured indoors may also originate outdoors, including emissions from natural and anthropogenic sources (e.g., vegetation, wildfires, traffic, and oil and gas extraction).

Identifying, quantifying, and apportioning sources of VOCs and understanding the factors that contribute to exposure scenarios are each crucial activities needed to establish strategies and policies that aim to reduce or minimize their release into the environment, and further, reduce human exposure to these compounds, if released. Historically, the impetus for measuring VOCs began with analysis of outdoor air; thus, the sampling methods were shaped by the VOC composition of outdoor air. As VOC sampling has moved indoors, the sampling methodologies have largely remained unchanged; yet it is unclear whether the select VOCs targeted by common analytical methods are always an appropriate match for what may be present in indoor air. While several studies have been conducted using receptor modeling approaches such as positive matrix factorization (PMF) and principal component analysis (PCA) to estimate source contributions of total measured VOC concentrations, relatively few studies have been conducted with weeklong sampling periods at a large quantity of diverse sites, collecting indoor and outdoor data, and accounting for 61 VOC compounds.

2. RATIONALE and OBJECTIVES

This study is a sub-study within a larger project initiated by the Colorado Department of Public Health and Environment (CDPHE) in collaboration with Colorado State University (CSU) to assess indoor air quality and ventilation in fifty workplaces across Colorado. The broader study aimed to evaluate air handling measures designed to reduce airborne COVID-19 risks and improve indoor environmental conditions in small workplaces, particularly in underserved communities. As part of this initiative, comprehensive indoor air quality (IAQ) and ventilation assessments were conducted, incorporating baseline data collection, recommendations for potential air handling upgrades, and follow-up evaluations to measure the effectiveness of implemented improvements.

Indoor air quality is a critical determinant of human health and well-being, particularly in workplaces where individuals spend a significant portion of their daily lives. Volatile organic compounds (VOCs) represent a major class of indoor air pollutants, originating from a diverse array of sources such as building materials, office equipment, cleaning products, and outdoor infiltration. The U.S. Environmental Protection Agency (EPA) has reported that indoor VOC concentrations are typically two to five times higher than outdoor levels, with certain activities causing spikes up to 1,000 times background concentrations. Prolonged exposure to VOCs is associated with a range of adverse health effects, from mild irritation to chronic respiratory conditions and, in the case of compounds like benzene and formaldehyde, carcinogenic risks.

Despite the increasing recognition of the importance of indoor air quality, much of the existing research has focused on residential environments, with comparatively fewer studies characterizing VOC exposures in workplaces. Offices, healthcare facilities, childcare centers, and other occupational settings present unique exposure scenarios due to differences in ventilation, occupancy patterns, and source distributions. While some research has assessed VOC presence in specific workplace types, comprehensive, long-duration monitoring across diverse occupational settings remains limited. Moreover, understanding the relative contributions of indoor sources versus outdoor infiltration is essential for designing effective mitigation strategies.

This study addresses a gap in understanding of VOC exposure risks in occupational settings by conducting an extensive characterization of VOC concentrations in a range of workplaces across Colorado. Over a two-year period, 50 workplaces were selected based on applications solicited by the Colorado Department of Public Health and Environment (CDPHE), prioritizing underserved communities. Indoor and outdoor air samples were collected using SUMMA canisters over weeklong periods and analyzed via EPA Method TO-15 to identify and quantify 61 target VOCs. To determine the primary sources of VOCs in these environments, the U.S. EPA's Positive Matrix Factorization (PMF) model was applied, allowing for statistical decomposition of measured concentrations into distinct source categories.

By integrating long-term sampling across diverse workplace environments with advanced source apportionment modeling, this study provides new insights into indoor VOC sources, their relative importance, and potential implications for exposure reduction. The results will inform building managers, policymakers, and environmental health professionals on targeted interventions to improve air quality in occupational settings. Ultimately, this work contributes to the broader field of exposure science by enhancing our understanding of indoor pollutant dynamics and supporting efforts to create healthier indoor environments.

3. LITERATURE REVIEW

Introduction to Indoor Volatile Organic Compounds and their Significance 3.1

Volatile organic compounds (VOCs) are a diverse group of chemicals that readily partition into the gas-phase at room temperature. Many VOCs can contribute to indoor air pollution. These compounds originate from both indoor and outdoor sources and can accumulate to levels that significantly impact human health and comfort. VOCs are emitted by a wide range of natural and anthropogenic sources, including vegetation, wildfires, traffic, volatile chemical products, and oil and gas extraction. VOCs play an important role in atmospheric chemistry by influencing atmospheric oxidative capacity, including the abundance of ozone (O_3), hydroxyl radicals, and hydroperoxides.[5] The importance of studying VOCs in indoor environments stems from the fact that people spend approximately 90% of their time indoors, making indoor air a dominant contributor to total VOC exposure. [6]According to the U.S. Environmental Protection Agency (EPA), indoor VOC concentrations may be two to five times higher than outdoor levels, with some activities indoors being associated with short-term spikes in VOC concentrations that further increase indoor levels relative to outdoor levels by many fold. [7] In the last several decades, a growing body of scientific evidence has shown that indoor air can be considerably more polluted than outdoors. [8]

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[5] I-Ting. Ku *et al.*, “Air quality impacts from the development of unconventional oil and gas well pads: Air toxics and other volatile organic compounds: Atmospheric Environment,” *Atmospheric Environment*, vol. 317, p. N.PAG–N.PAG, Jan. 2024

[6] D. Campagnolo *et al.*, “VOCs and aldehydes source identification in European office buildings - The OFFICAIR study,” *Building and Environment*, vol. 115, pp. 18–24, Apr. 2017

[7] D. Pan *et al.*, “Source characterization of volatile organic compounds at Carlsbad Caverns National Park,” *Journal of the Air & Waste Management Association*, vol. 73, no. 12, pp. 914–929, Oct. 2023

[8] D. E. Saraga *et al.*, “Source apportionment for indoor air pollution: Current challenges and future directions,” *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023

Workplace environments present unique exposure scenarios compared to residential settings. While homes are characterized by emissions from cooking, personal care products, and household cleaning agents, workplaces often feature emissions from building materials, office equipment, maintenance products, and industrial processes. Variability in ventilation rates, occupancy patterns, and space utilization further differentiates workplace VOC exposure from residential environments. Given the wide range of occupational settings, it is important to characterize VOC sources and concentrations indoors across this diverse range of settings to better understand whether and to what extent VOCs measured indoors contribute to and possibly elevate total VOC exposure.

Sources and Characteristics of Indoor VOCs 3.2

Building Materials and Furnishings 3.2.1

Many VOCs found indoors originate from the off gassing of building materials, furniture, flooring, adhesives, and paints. Formaldehyde, benzene, and toluene are among the most common emissions from pressed wood products, carpeting, and coatings. Studies have shown that recently renovated buildings tend to have higher VOC concentrations due to the elevated emission rates of VOCs from new materials. [9] Over time, VOC emission rates typically decrease, but some materials continue to release compounds for years after installation.

Office Equipment and Consumer Products 3.2.2

Office environments introduce additional VOC sources, particularly from printers, copiers, and electronic devices, which emit solvents, ozone, and fine particulate matter. Toner-based printing equipment has been identified as a significant source of benzene, styrene, and

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[9] N. B. Goodman, A. J. Wheeler, P. J. Paevere, P. W. Selleck, M. Cheng, and A. Steinemann, “Indoor volatile organic compounds at an Australian university,” *Building and Environment*, vol. 135, pp. 344–351, May 2018.

formaldehyde. Additionally, workplace cleaning agents, air fresheners, and personal care products used by employees contribute to VOC levels, with terpenes such as limonene and alpha-pinene being among the most frequently detected compounds.

The OFFICAIR study[10], a comprehensive investigation into volatile organic compounds (VOCs) and aldehyde sources in European office buildings, highlighted key factors influencing indoor air quality. This study systematically assessed various parameters during field visits, paralleling aspects of the fieldwork conducted in the present research. Specifically, the OFFICAIR study collected data on general building characteristics (such as construction and renovation periods, geographic location, and room design), office-specific features (building and furniture materials, office equipment, and ventilation systems), and occupant behaviors (cleaning practices, frequency of specific activities, and use of office-related products like printers and chemical cleaners). These findings underscored the role of office equipment and workplace behavioral patterns as major contributors to indoor VOC concentrations. Frequent printer use, for example, has been linked to emissions of benzene, styrene, and formaldehyde, while cleaning agents contribute to elevated levels of terpenes and oxygenated VOCs.

The implications of the OFFICAIR study align with those of other large-scale workplace air quality investigations. Goodman et al. (2018)[11] examined VOC emissions in an Australian university setting, identifying office equipment and cleaning products as dominant sources of indoor air pollutants. Similarly, Saraga et al. (2023)[12] explored source apportionment for indoor

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[10] D. Campagnolo *et al.*, “VOCs and aldehydes source identification in European office buildings - The OFFICAIR study,” *Building and Environment*, vol. 115, pp. 18–24, Apr. 2017

[11] N. B. Goodman, A. J. Wheeler, P. J. Paevere, P. W. Selleck, M. Cheng, and A. Steinemann, “Indoor volatile organic compounds at an Australian university,” *Building and Environment*, vol. 135, pp. 344–351, May 2018

[12] D. E. Saraga *et al.*, “Source apportionment for indoor air pollution: Current challenges and future directions,” *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023

VOCs and found that a significant fraction of measured compounds originated from human activities and product use rather than external infiltration. These studies reinforce the necessity of accounting for both building-related and occupant-driven emissions when evaluating workplace VOC exposure.

The present study builds upon these findings by applying extended, week-long VOC sampling and source apportionment modeling across multiple workplaces, further elucidating the role of workplace-specific factors in determining indoor air quality. The results contribute to a growing body of evidence demonstrating that while ventilation and building materials influence air quality, occupant behaviors and equipment usage play equally critical roles in shaping indoor VOC profiles.

Combustion Processes and Industrial Activities 3.2.3

Certain workplaces, including healthcare facilities, laboratories, and light industrial environments, are subject to VOC emissions from combustion processes and industrial solvents. Laboratories and medical offices may have additional exposures from disinfectants, sterilizers, and volatile anesthetic gases.[13] Meanwhile, combustion-based sources such as heating systems, vehicle exhaust infiltration, and commercial kitchens introduce a mixture of alkanes, aromatic hydrocarbons, and oxygenated VOCs.

Acrolein is produced by the incomplete combustion of organic material as well as the oxidation of atmospheric chemicals. Indoor sources of acrolein related to human activities include heated cooking oil, cigarette smoke, burning incense and wood-burning fireplaces. In addition to emissions from human activities, acrolein and other carbonyls are known to off-gas

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[13] E. Kabir, K.-H. Kim, J.-W. Ahn, O.-F. Hong, and J. R. Sohn, “Barbecue charcoal combustion as a potential source of aromatic volatile organic compounds and carbonyls,” *Journal of Hazardous Materials*, vol. 174, no. 1–3, pp. 492–499, Feb. 2010.

from building materials and are also formed from the oxidation of volatile organic carbon species released by building materials.[14]

Outdoor Infiltration and Environmental Factors 3.2.4

Outdoor VOC sources, including traffic emissions, industrial discharges, and biogenic sources, can infiltrate indoor environments through ventilation systems, windows, doors, and leakage across the building envelope. In urban settings, benzene, toluene, ethylbenzene, and xylenes (BTEX compounds) are frequently detected indoors because of vehicle exhaust infiltration. Oil and gas extraction activities can also contribute to elevated indoor VOC concentrations in regions with active drilling and refining operations. Seasonal variations in temperature and humidity influence VOC concentrations, with higher emissions typically observed in warmer months due to increased volatilization.

U.S. UOGD (Unconventional oil and gas development) occurs in both rural and populated regions and growing development has raised concerns about impacts on the environment and human health. Numerous studies have examined methane emissions from the O&G industry; fewer studies have examined emissions and air quality impacts of O&G VOCs. [15]An analysis utilizing measured emissions distributions, regional meteorological conditions, and dispersion modeling simulations assessed human health risks from exposure to VOCs emitted from O&G operations informed statewide implementation of a 2000-foot (610-m) setback distance to better protect residential populations. Long-term air toxics observations around O&G

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[14] V. Y. Seaman, D. H. Bennett, and T. M. Cahill, “Indoor acrolein emission and decay rates resulting from domestic cooking events,” *Atmospheric Environment*, vol. 43, no. 39, pp. 6199–6204, Dec. 2009

[15] A. Hecobian *et al.*, “Air Toxics and Other Volatile Organic Compound Emissions from Unconventional Oil and Gas Development,” *Environmental Science & Technology Letters*, vol. 6, no. 12, pp. 720–726, Oct. 2019.

operations, however, are needed to assess the accuracy of modeled concentration fields and exposures.[16]

Health Impacts of Indoor VOC Exposure 3.3

Exposure to volatile organic compounds (VOCs) has been associated with a range of adverse health effects, from acute symptoms such as headaches, eye irritation, dizziness, and respiratory discomfort to long-term consequences including chronic respiratory diseases, neurological impairments, and carcinogenicity. The severity of these health impacts depends on multiple factors, including the concentration of specific VOCs, duration and frequency of exposure, and individual susceptibility. Given that individuals spend a significant portion of their time indoors—whether in homes, workplaces, or other microenvironments—indoor air pollution plays a critical role in overall exposure. This is particularly concerning for vulnerable populations, such as children, the elderly, and individuals with preexisting health conditions, who may experience heightened sensitivity to VOC exposure.

Because indoor air quality is influenced by both indoor emission sources and outdoor infiltration, distinguishing between these contributions is crucial for accurate health risk assessment. Identifying primary VOC sources enables the development of evidence-based regulatory guidelines and targeted intervention strategies. Effective mitigation approaches—such as optimizing ventilation, substituting high-emission consumer products, and implementing source control measures—are essential to reducing indoor pollutant levels and minimizing human health risks associated with VOC exposure.[17]

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[16] I-Ting. Ku *et al.*, "Air quality impacts from the development of unconventional oil and gas well pads: Air toxics and other volatile organic compounds: Atmospheric Environment," *Atmospheric Environment*, vol. 317, p. N.PAG–N.PAG, Jan. 2024

[17] D. E. Saraga *et al.*, "Source apportionment for indoor air pollution: Current challenges and future directions," *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023

Short-term health effects 3.3.1

Short-term exposure to elevated VOC levels can cause sensory irritation and adverse effects on cognitive function. Studies have demonstrated that high concentrations of VOCs, particularly in office environments with poor ventilation, can impair decision-making and reduce worker productivity. Additionally, acute exposure to certain solvents can lead to dizziness, nausea, and respiratory discomfort.

Acute exposure to VOCs has been linked to an increased risk (0.86–1.25%) of hospitalization for respiratory diseases, such as asthma and chronic obstructive pulmonary disease. Long-term exposure to VOCs has been associated with cardiovascular diseases, neurological disorders, and preterm births. Certain VOCs, including benzene and formaldehyde, can pose a lifetime cancer risk via different exposure routes (i.e., inhalation, oral, and dermal) and have been classified as known and probable human carcinogens by the United States Environmental Protection Agency (U.S. EPA)[18]

Long-term health effects and chronic exposure risks 3.3.2

Long-term VOC exposure is associated with more serious health concerns, including increased risks of asthma, chronic obstructive pulmonary disease (COPD), and certain cancers. Benzene, a well-documented human carcinogen, has been linked to leukemia, while formaldehyde exposure is associated with nasopharyngeal cancer and respiratory sensitization. Studies have shown that individuals with prolonged exposure to VOC-rich environments, such as workers in manufacturing plants or beauty salons, experience higher incidences of respiratory and neurological disorders.

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[18] Y. Xiong, K. Du, and Y. Huang, “One-third of global population at cancer risk due to elevated volatile organic compounds levels,” *npj Climate and Atmospheric Science*, vol. 7, no. 1, pp. 1–11, Mar. 2024

A study looking into cancer risk for the global population due to elevated VOC levels, found that, "Carcinogenic VOCs such as benzene, formaldehyde, and acetaldehyde contributed to a lifetime cancer burden affecting 0.60 [95% confidence interval (95CI): 0.40–0.81] to 0.85 [95CI: 0.56–1.14] million individuals globally. We projected that between 36.4% and 39.7% of the global population was exposed to harmful VOC levels, with the highest exposure rates found in China (82.8–84.3%) and considerably lower exposure in Europe (1.7–5.8%). Significant disparities in cancer burdens between high-income and low-to-middle-income countries were identified throughout the study period, primarily due to unequal population growth and VOC emissions. These findings underscore health disparities among different income nations and emphasize the persistent need to address the environmental injustice related to air pollution exposure." [19] Results are particularly important and significant for less developed regions with limited VOC monitoring networks and a general lack of awareness regarding air pollution, as they provide valuable insights on how to mitigate outdoor VOC pollution and attain health and economic benefits.[17]

Indoor VOC Monitoring and Measurement Techniques 3.4

The accurate measurement of indoor VOCs is essential for exposure assessment and mitigation strategies. Various sampling techniques have been employed to quantify VOC concentrations in different settings.

Active and passive sampling methods 3.4.1

VOC sampling can be conducted using both active and passive methods. Active sampling involves the use of pumps to collect air samples over a specified period, typically onto sorbent tubes or canisters, followed by laboratory analysis. Passive sampling relies on diffusion-based

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[19] Y. Xiong, K. Du, and Y. Huang, "One-third of global population at cancer risk due to elevated volatile organic compounds levels," *npj Climate and Atmospheric Science*, vol. 7, no. 1, pp. 1–11, Mar. 2024

uptake of VOCs onto sorbents, offering a cost-effective and low-maintenance approach for long-term monitoring.

A study out of Building and Environment suggests that passive samplers have been proposed as simple and inexpensive tool to measure emissions of VOCs from buildings and furnishing materials. The samplers can be used to pinpoint strong emitters of pollutants, which helps to design efficient strategies to improve indoor air quality. There is a need for inexpensive and easy to use devices that can be used in-site to identify emitting materials and to quantify the associated emissions. Hence passive sampling meeting the requirements of inexpensive and simple to use.[20]

Analytical techniques 3.4.2

Gas chromatography-mass spectrometry (GC-MS) is the gold standard for VOC analysis, providing high sensitivity and specificity for identifying individual compounds. The EPA Method TO-15, employed in this study, utilizes SUMMA canisters to collect whole-air samples for subsequent GC-MS analysis. Other analytical methods, such as proton-transfer reaction mass spectrometry (PTR-MS) and real-time sensors, offer alternative approaches for VOC quantification in research and regulatory applications.

Source Apportionment and Positive Matrix Factorization 3.5

Source apportionment (SA) for indoor air pollution is challenging due to the multiplicity and high variability of indoor sources, the complex physical and chemical processes that act as primary sources, sinks and sources of precursors that lead to secondary formation, and the interconnection with the outdoor environment. While the major indoor sources have been

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[20] G. Poulhet, S. Dusanter, S. Crunaire, N. Locoge, P. Kaluzny, and P. Coddeville, “Recent developments of passive samplers for measuring material emission rates: Toward simple tools to help improving indoor air quality,” *Building and Environment*, vol. 93, pp. 106–114, Nov. 2015

recognized, there is still a need for understanding the contribution of indoor versus outdoor-generated pollutants penetrating indoors, and how SA is influenced by the complex processes that occur in indoor environments.[21] Identifying the sources of indoor VOCs is critical for developing effective mitigation strategies. Receptor models, such as Positive Matrix Factorization (PMF), provide a statistical approach for apportioning measured VOC concentrations to distinct source categories without requiring predefined source profiles. Identifying and apportioning sources of VOCs and understanding factors contributing to exposures are needed to establish strategies and regulatory policies in order to reduce or minimize their release into the environment. Several studies have been carried out worldwide to understand the indoor determinants of VOCs mostly in a qualitative way by using univariate and multivariate analyses, variance component analyses, linear regression models, mixed effect models and other techniques.[22]

Application of PMF in indoor air quality studies 3.5.1

PMF has been widely applied in air quality research to distinguish between various VOC sources, including traffic emissions, industrial activities, and indoor product use. By resolving complex datasets into interpretable factor profiles, PMF allows researchers to determine the relative contributions of different sources. In previous studies, PMF has been used to separate indoor VOC sources related to cleaning products, cooking emissions, and solvent-based materials.

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[21] D. E. Saraga *et al.*, “Source apportionment for indoor air pollution: Current challenges and future directions,” *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023

[22] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, “Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada,” *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

Receptor-oriented models can be applied to identify emission sources and estimate contributions of all identified sources to total measured VOC concentrations in the period of interest. Different receptor modeling approaches e.g., positive matrix factorization (PMF), chemical mass balance (CMB), principal component analysis (PCA) and absoluate principal component scores (APCS) have been widely used to estimate source contributions to ambient VOC concentrations. However, relatively few receptor modeling attempts have been made using PCA and PMF to identify and apportion indoor and outdoor sources of VOCs using a single day measurement at multiple homes. In comparison with PCA, PMF produces a better fit to the data and provides non-negative factors, error estimates and better data treatment including missing values and below detection limit and has been widely used for source apportionment of ambient VOCs. Uncertainty estimation is an important step in PMF, where each of the data values is assigned, an estimated uncertainty including both measurement uncertainty and source profile variability.[23]

Alternative Source Apportionment Methods 3.5.2

While PMF is a robust tool for source identification, other statistical approaches such as principal component analysis (PCA) and chemical mass balance (CMB) modeling have also been utilized in indoor air studies. PCA provides insight into co-variability between VOCs, while CMB relies on predefined source profiles to apportion emissions. Recent advancements in receptor modeling have explored hybrid techniques that integrate multiple methods to improve source resolution.

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[23] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, “Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada,” *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

A study out of Edmonton, Canada shared insights on how the optimal number of factors were chosen using PMF, as well as other source apportionment methods to compare factor solutions. This methodology will be utilized for factor solution decision making. "The optimal number of factors was chosen after analyzing several model performance criteria e.g., goodness-of-fit Q-values for the entire run, scaled residual matrices, scatter plots between species, agreement between predicted and measured mass, and physical meaningfulness of the source profiles and contributions. The FPEAK solutions were checked and the base run yielded the optimum solution. To quantify precision of the PMF results (i.e., reproducibility of the solution), a bootstrapping analysis was implemented. A total of 100 bootstrap runs were performed with a minimum r^2-value of 0.6. Of the 100 runs, all identified factors were mapped to a base factor in every run indicating a stable and robust solution." [24]

Summary of Knowledge and Research Gaps 3.6

Despite significant advancements in understanding indoor VOC exposures, several gaps remain. Limited long-term monitoring studies have been conducted in workplaces, particularly in underserved communities. Additionally, while PMF for VOC source apportionment has been applied to a limited extent in some indoor environments, its use in workplace settings remains underexplored. This study aims to address these gaps by providing a comprehensive characterization of workplace VOC sources, utilizing extensive weeklong sampling and advanced statistical modeling to inform indoor air quality management and policy development.

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[24] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015.

4. METHODS

Study Design 4.1

Study Context 4.1.1

In the wake of the COVID-19 pandemic, the Colorado Department of Public Health and Environment (CDPHE) partnered with a team in Civil and Environmental Engineering at Colorado State University to assess and characterize indoor air quality across underserved workplaces in Colorado. Workplace selection criteria and process can be found in Site Selection 4.1.2. Ultimately, fifty unique workplaces from across the state of Colorado were chosen to participate in this study. Figure 1 below depicts the locations of the participating sites.

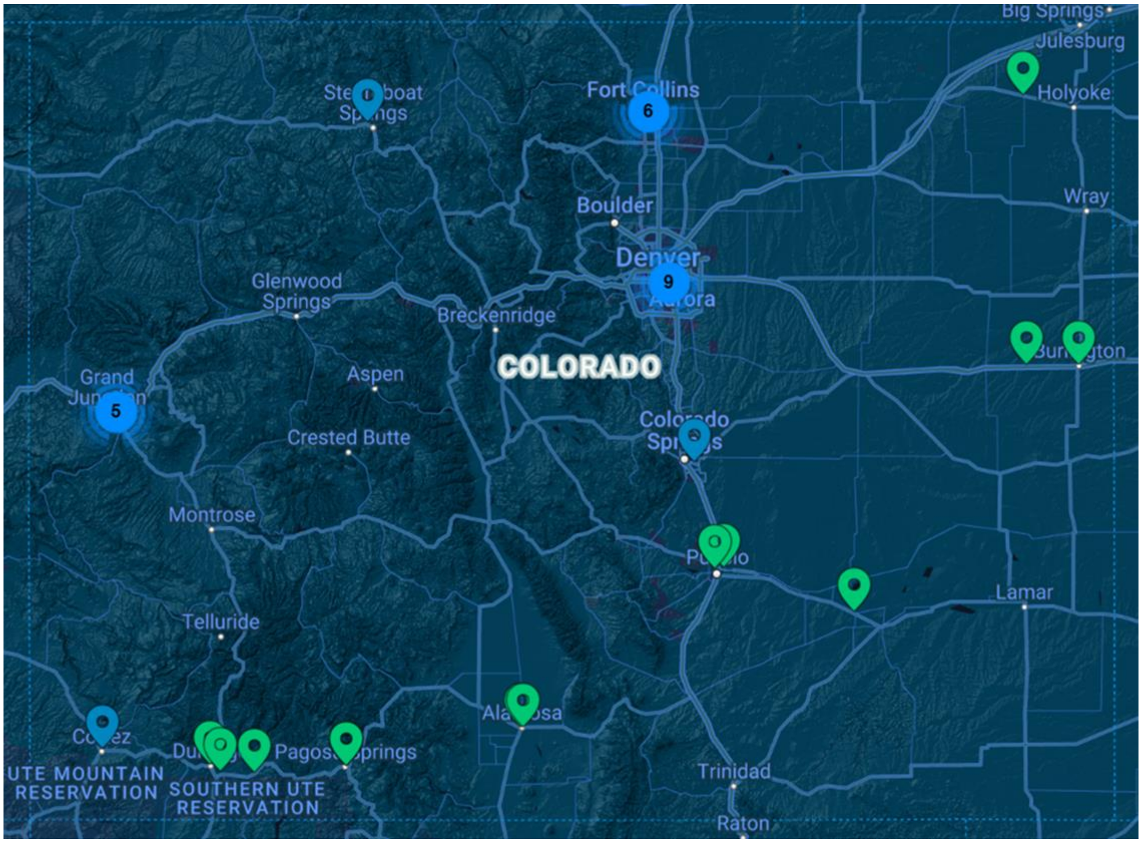

Figure 1: Map displaying the study area.

Site Selection 4.1.2

Sites were selected using a scoring matrix developed by the Colorado Department of Public Health and Environment, with input provided by CSU researchers. All applicants to the study received a score, which considered the following factors: size, equity, rural/non-rural, facility type and impact. Size was based on the number of occupied rooms at the site, equity was based on Social Vulnerability Index (SVI), what type of population the building served and the organization ownership. Rural vs non rural was based upon the rural designation list, facility type was scored according to the NAICS code list, and impact was determined based on access to other known resources, total occupants per week and the type of HVAC the site has. This scoring matrix was established to ensure that facilities included in the study would have a high likelihood to benefit most from the indoor air quality and ventilation assessments and resulting insights related to interventions identification and implementation intended to follow the indoor air quality and ventilation assessment period (though outside the scope of the project).

Site Measurements 4.1.3

At each site, the indoor and outdoor air quality measurements were conducted for 14 consecutive 24-hour periods. Worksites were sampled individually and at varying times of the year, with some sites being measured concurrently pending coordination with the work site representative. Three to five measurement locations were identified at each site depending on site size and setup with respect to differentiable room types. Measurements relevant to the work presented in this thesis included time-integrated, gas-phase air sampling with SUMMA canisters (Entech Instruments, USA). In addition to these measurements, a wide range of other time-integrated and continuous particle and gas sampling was conducted that will not be described herein. Additionally, an outdoor air quality measurement station was set up, often on the rooftop of the site, which also included a SUMMA canister (in addition to other time-integrated and continuous particle and gas sampling devices analogous to those used indoors). Furthermore, each site's air handling system was evaluated to determine layout, organization, and building air flow characteristics. Airflow sensors used included Retrotecs, TrueFlow DG-8, Dwyers, TSI AirPro and TF Grids. LiDAR was also used to obtain a point cloud, 3-D representation of each site. Study participants were asked to continue with their normal activities during the sampling periods to ensure that measurements were reflective of typical workspace activities.

After facilities were recruited and selected into the program by CDPHE, facility representatives received an initial survey, which served as the primary tool for planning site visits. Site visits were typically expected to take between one and three days, including a question-and-answer session with facility staff, a site walk-through, one-time measurements, and the installation of equipment for longer-term measurements. The site walk-through with a building representative often provided additional information complementary to that which was obtained with the CDPHE baseline intake survey. Furthermore, the site walk-through yielded insight about room level occupancy and time activity patterns of occupants that assisted the preparation for site-level measurements. Follow-up assessments took place on an as-needed basis to understand the longer-term performance of the facilities, verify models of air handling systems, and – at the request of the facility – to assess the impact of changes to air handling at the facility, if any were made following the initial assessment.

The initial assessment aimed to comprehensively evaluate workplace ventilation, indoor air quality, building characteristics, and occupancy patterns. A key objective of this broader indoor air quality and ventilation assessment program was to characterize the potential for COVID-19 transmission within these environments. Additionally, the assessment established baseline measurements necessary for determining whether, and to what extent, modifications to building infrastructure or air handling systems—if implemented by the workplace—would influence indicators associated with airborne disease transmission.

The baseline indoor air quality and ventilation assessments played a critical role in identifying potential improvements to ventilation systems and operational strategies. They also provided insights into the relationship between indoor and outdoor air quality at each facility. Furthermore, these assessments supplied essential data for airflow and air quality modeling, allowing for a more comprehensive evaluation of how each facility performs under various operational and environmental conditions.

The ventilation system of each building was assessed to evaluate how the facility was designed to provide airflow, the performance of mechanical ventilation serving occupied spaces, and overall air infiltration. During ventilation and air leakage testing, the system was set to operate at a constant supply airflow rate. Before measurements began, the system was allowed to run for at least 15 minutes to stabilize conditions, and all windows were closed to prevent external airflow interference.

In each applicable room, several key parameters were measured, including central supply and return airflow rates, local supply and exhaust airflow rates, and the number of openable windows. Additionally, the source and destination of central air distribution were identified. Temperature, humidity, and pressure within each air supply duct were recorded in the facility room log. The total number of central air handlers and the rooms they serviced were documented, along with any room-level air treatment systems in use.

At each facility, outdoor air change rates were estimated by analyzing the natural decay of carbon dioxide (CO_2) concentrations that accumulated due to occupants' respiration. The air change rate (ACH) represents the number of times per hour that the total volume of air within a space is replaced by ventilation, including both mechanical and natural air exchange. To estimate ACH, CO_2 mixing ratios were continuously monitored using Q-Trak instruments, capturing real-time fluctuations in indoor concentrations.

The evaluation was conducted under well-mixed conditions at both the beginning and end of the measurement period, with particular attention given to periods when occupancy levels changed significantly. When possible, data collection was performed during unoccupied periods to isolate ventilation-driven CO_2 decay from continued human respiration. The decay of CO_2 from elevated concentrations back to near-background levels (typically ~400–700 ppmV) was analyzed to estimate the effective air change rate, incorporating both mechanical ventilation and natural air exchange.

Additionally, detailed building information was collected using LiDAR scans of each facility's interior. To ensure accuracy and efficiency, the scanning route was carefully planned to minimize redundant data collection, beginning and ending at the same location while avoiding personnel in the scanned areas. The point-cloud data generated from the scans were processed using CAD software to extract precise building dimensions and spatial characteristics. A separate scan of the building exterior was performed to develop a basic structural profile of each facility, complementing the interior dataset.

VOC Measurement 4.1.4

VOC concentrations were a key component of the indoor air quality measurements collected in this study. However, VOC sampling was not conducted at all participating sites due to budgetary and labor constraints. Once it was determined that VOC sampling could feasibly be included within the project scope, all subsequent sites incorporated VOC measurements, with the exception of a few locations where resource limitations prevented deployment.

At sites where VOC sampling was conducted, an additional site visit was required, as the deployment of VOC measurement devices did not begin until the seventh day of the standard fourteen-day measurement period. After seven days of sampling, a team member returned to retrieve the VOC monitoring equipment. This visit also marked the conclusion of data collection at the site, as all other air quality and ventilation measurements had already been completed.

During this final visit, general feedback was gathered from site representatives regarding the measurement process, and all deployed instruments were removed.

The following figure (Figure 2) presents an overview of the sites where VOC sampling was conducted.

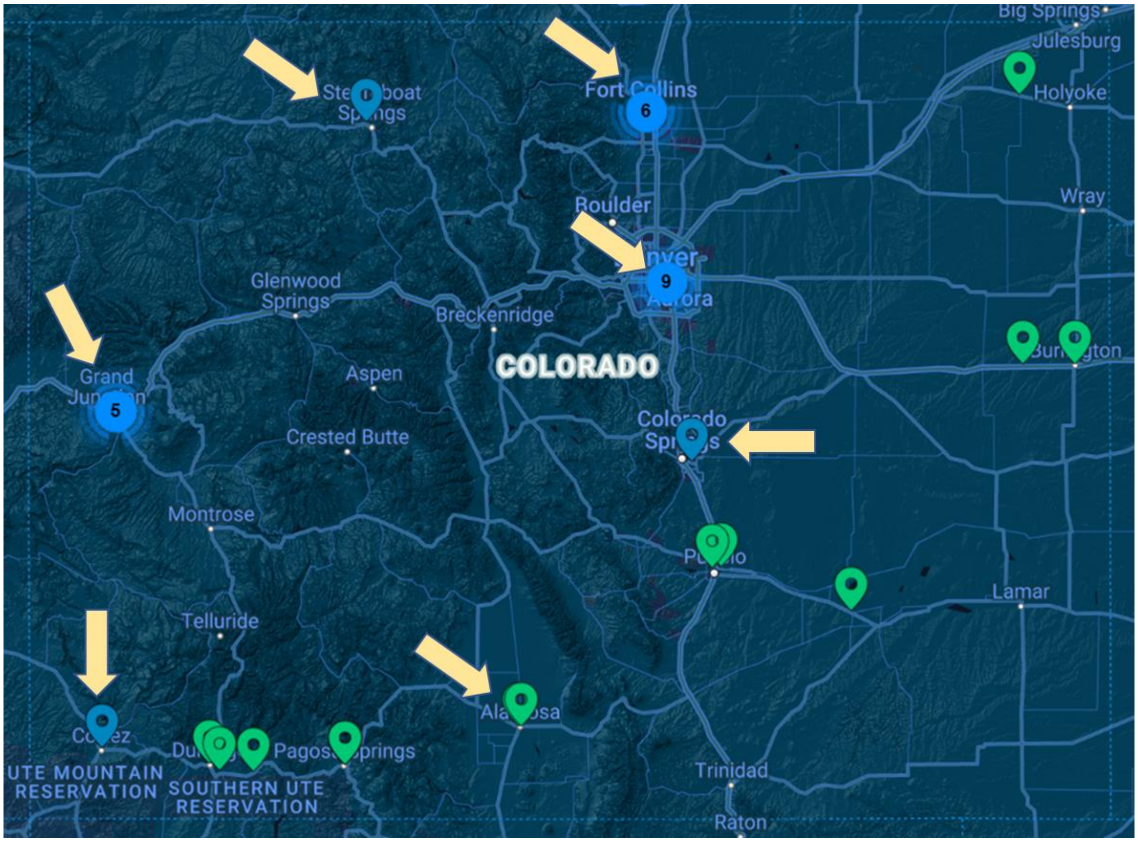

Figure 2: Map displaying sites sampled for VOCs

VOC Sampling and Analysis 4.2

VOC sampling 4.2.1

At approximately one third of the sites included in the study, stainless steel 6.0 L Silonite coated stainless steel SUMMA Canisters (Entech Instruments) coupled with CS1200E flow regulation systems were deployed for seven consecutive 24-hour periods. SUMMA canisters were installed after the first 7-day period of measurement and were retrieved at the end of the 14-day study period. The flow control system allowed for each canister to slowly fill over the 7-day sampling period. SUMMA canisters were used to collect air samples passively and non-selectively. Both indoor and outdoor samples were analyzed by Colorado State Universities Atmospheric Science department researchers. Canisters were cleaned using an Entech 3100 canister cleaning system prior to field deployment by evacuating the canister to 10^{-2} torr and purging with ultra-high purity nitrogen for 8 cycles at 80 degrees C.[25] Prior to sampling and per US EPA Method TO-15 each canister was evacuated to an initial negative pressure around -30mm mercury. During the sample period, the vacuum inside the canister was replaced with air at a constant flow rate (3.5 mL/min) by the means of flow controllers.

VOC Analysis 4.2.2

SUMMA canister air samples, specifically methane and VOCs in each canister sample were analyzed at the Colorado State University Atmospheric Science Department via gas chromatography (GC). Methane was analyzed using a Shimadzu GC-8A equipped with a digital temperature programmer and flame ionization detector (FID). The analytical column consisted of two 6’ x 1/8” O.D. stainless steel columns packed with Porapak Q. Samples were injected at

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[25] I-Ting. Ku *et al.*, “Air quality impacts from the development of unconventional oil and gas well pads: Air toxics and other volatile organic compounds: Atmospheric Environment,” *Atmospheric Environment*, vol. 317, p. N.PAG–N.PAG, Jan. 2024

room temperature, and the column oven temperature was held at 40°C. Ultra-high purity nitrogen (Airgas Inc., NI UHP300) was used as a carrier gas and zero air (Airgas Inc., AI UZ300) plus ultra-high purity hydrogen (Airgas Inc., Hy UHP300) was supplied to the FID. A methane standard (SCOTT-MARRIN Inc., CA, USA), 20.41±1% ppmv in ultrapure nitrogen, was used to calibrate the working standard. At least five working standard injections were analyzed in each analysis batch to assess system drift or malfunction. The methane measurement precision (1 relative standard deviation, RSD) was 4%. The methane method detection limit (MDL) was 0.206 ppmv. [2]

Sixty-one VOCs were measured in each canister sample using a custom, multi-channel GC system by CSUs Atmospheric Science department using systems described in previous studies. [26] This system included three GCs and five detectors (three FIDs, one electron capture detector (ECD) and one mass spectrometer (MS)). Calibration was conducted using a certified mixed hydrocarbon standard (HC Mix56, Airgas, PA, USA). Working standards were analyzed during each analysis to check system drift and to derive VOC response factors.

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[26] K. B. Benedict *et al.*, "Volatile organic compounds and ozone in Rocky Mountain National Park during FRAPPÉ," *Atmospheric Chemistry and Physics*, vol. 19, no. 1, pp. 499–521, Jan. 2019
Y. Zhou *et al.*, "Coastal water source of short-lived halocarbons in New England," *Journal of Geophysical Research*, vol. 110, no. D21, Nov. 2005
B. C. Sive *et al.*, "Development of a Cryogen-Free Concentration System for Measurements of Volatile Organic Compounds," vol. 77, no. 21, pp. 6989–6998, Sep. 2005

Descriptive Data Analysis 4.3

Descriptive statistics 4.3.1

Following the collection of VOC data from SUMMA canisters, primary data analysis was conducted using RStudio to quantify trends and identify key contributors to indoor air quality. The analysis included calculating summary statistics at both the site and room level, as well as generating visual representations of VOC concentration patterns. This approach allowed for the identification of the most dominant analytes across different sampling locations and room types.

To assess the primary contributors to VOC concentrations, the top ten most prevalent analytes were identified for both indoor and outdoor measurements. These analytes were plotted to compare their concentration magnitudes and determine which species appeared most frequently in high concentrations across different environments. Additionally, VOC concentrations were analyzed by room type, with a particular focus on kitchen spaces, healthcare facilities, recreational areas, and temporary housing shelters. This analysis was designed to explore whether specific site characteristics played a notable role in influencing indoor air quality.

To further evaluate the relationship between indoor and outdoor VOC concentrations, indoor-to-outdoor (I/O) concentration ratios were calculated. These ratios provided insight into the extent to which indoor concentrations exceeded outdoor levels, helping to distinguish VOCs primarily driven by indoor sources from those influenced by outdoor infiltration.

Indoor outdoor ratios 4.3.2

Indoor-to-outdoor (I/O) concentration ratios were used to assess the extent of air exchange and mixing between indoor and outdoor environments for various VOC species. These ratios provide insight into whether specific compounds are predominantly generated indoors or if outdoor sources contribute significantly to indoor air composition.

To calculate I/O ratios, indoor and outdoor VOC concentration data were compiled into a structured data frame in RStudio. The ratio for each analyte was computed by dividing the mean indoor concentration by the corresponding mean outdoor concentration. To facilitate comparisons across all sites, mean VOC concentrations were calculated separately for indoor and outdoor samples. For example, all indoor toluene measurements from every site were aggregated into a single mean value representing overall indoor toluene levels, and the same process was applied for outdoor measurements.

Based on prior literature, I/O ratios were expected to vary widely, potentially reaching values as high as 1,000 in cases where indoor concentrations were significantly elevated due to high-exposure activities such as solvent use or cooking. However, the majority of species were anticipated to have I/O ratios greater than one, indicating a dominant indoor source, while relatively few were expected to exhibit ratios below one, which would suggest a stronger outdoor influence.

Prevalence of Individual VOC species 4.3.3

To determine the most prevalent volatile organic compounds (VOCs) measured indoors across all sampled workplaces, a systematic approach was employed to ensure that the selected compounds were consistently elevated in concentration and widely detected. The analysis was based on measurements taken in 84 rooms across the total of 18 workplaces included in the study, resulting in a total of 5,124 indoor samples. The following steps describe the methodology used to identify and rank the top ten VOC analytes.

First, all indoor VOC measurements collected using SUMMA canisters and analyzed via EPA Method TO-15 were compiled into a structured dataset. The dataset included compound-specific concentrations for each of the 5,124 indoor samples. Any non-detect values were handled using their respective limit of detection to ensure that the reported top ten VOCs reflected real and substantial indoor air concentrations rather than artifacts of detection limits or instrument sensitivity.

To establish a defensible ranking of the top ten VOCs, three key criteria were considered: (1) frequency of detection across all sampled rooms, (2) central tendency of measured concentrations, and (3) magnitude relative to outdoor concentrations where applicable. First, the detection frequency was calculated for each analyte as the percentage of indoor samples in which the compound was detected at or above its MDL. Analytes that were detected in fewer than 25% of samples were excluded from further ranking, as low detection frequency would suggest irregular or incidental presence rather than consistent indoor prevalence.

For the remaining compounds, a ranking procedure based on central tendency measures was applied. The geometric mean concentration was selected as the primary metric to characterize the typical indoor level of each analyte. The geometric mean was used rather than the arithmetic means to reduce the influence of extreme values and better represent a compound's consistent presence across multiple locations. Geometric means were calculated for each analyte across all indoor measurements, and the ten compounds with the highest geometric means were identified as leading candidates for the top ten list.

To further refine the ranking, the relative magnitude of indoor concentrations compared to outdoor levels was evaluated using indoor-to-outdoor (I/O) concentration ratios. Outdoor measurements were available from co-located sampling, allowing for direct comparison. VOCs with an average I/O ratio greater than one were prioritized, as this indicated that their presence indoors was primarily driven by indoor sources rather than outdoor infiltration. Compounds with consistently high concentrations but low I/O ratios (suggesting strong outdoor origins) were carefully reviewed to determine whether they should be included in the final top ten ranking.

Finally, the robustness of the ranking was assessed by performing sensitivity analyses. The ranking was re-evaluated using alternative statistical measures, such as arithmetic means, to confirm that the identified top ten VOCs remained among the most dominant compounds across different statistical approaches. Additionally, the top ten ranking was cross validated across different workplace types to ensure that it was not overly influenced by any single category of workplace.

The final top ten VOCs were reported in a ranked list based on geometric mean concentration, with detection frequency and I/O ratios included as supporting metrics. This method provides a clear and reproducible approach to identifying the most prominent indoor VOCs, ensuring that the selected compounds are representative of indoor air quality trends across diverse workplace environments.

Positive Matrix Factorization 4.4

Protocol 4.4.1

A multivariate receptor model, namely, the US EPA positive matrix factorization (PMF) 5.0 program, was applied to the VOC dataset to elucidate and apportion potential sources of VOCs in the indoor environments included in this study. PMF is a multivariate technique based on weighted least squares fit, in which weights are derived from the analytical uncertainties.[27]

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[27] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, “Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada,” *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

Prior to the input of data to the PMF model, uncertainties were estimated, including both measurement uncertainty and source profile variability. For each recorded VOC value, if the concentration recorded was less than the limit of detection for that analyte, 5/6*LOD was used as the uncertainty value. If the concentration recorded was greater than the LOD, the uncertainty value used was .1*concentration reported. In the observed values matric, zeros were inputted for missing values. When inputting data to the PMF tool, this was noted for the program to recognize as zero values. A Principal Component Analysis was also conducted in RStudio prior to PMF modeling to gain a base understanding of strong factor solutions. Scree plots were used to supplement decision making regarding which factor solution is most representative of the data sample.

The following figure (Figure 3) depicts the parameters utilized to build out the uncertainty data matrix required by the EPA PMF tool.

$$\text{Uncertainty} = \begin{cases} \frac{5}{6} \times \text{Limit of Detection} & \text{if Conc.} < \text{Limit of Detection} \\ 0.1 \times \text{Conc.} & \text{if Conc.} \geq \text{Limit of Detection} \end{cases}$$

Figure 3: Parameters for Uncertainty Matrix

Principal Component Analysis (PCA) and Positive Matrix Factorization (PMF) models were applied using various data segmentation strategies to evaluate their influence on factor separation. One key approach involved running models with and without outdoor VOC data to determine how the inclusion of outdoor measurements affected factor resolution. This comparison helped assess the extent to which outdoor sources contributed to the identified VOC factors and whether excluding outdoor data improved the differentiation of indoor-specific sources.

To further explore site-specific influences, the dataset was separated based on room type, specifically distinguishing kitchen spaces from other indoor environments. Two matrices were created: one excluding kitchen-type rooms and another including only kitchen-type rooms. This distinction was necessary because cooking activities are well-documented as major contributors to VOC emissions, and their inclusion could strongly influence factor differentiation.

Seasonal variations were also examined by dividing the dataset into cool-season and warm-season subsets. Seasonal differences can significantly impact VOC concentrations due to factors such as temperature-driven volatilization and wildfire events, particularly in the summer and fall months. By analyzing seasonal subsets separately, the models accounted for these variations and their influence on VOC source attribution.

Additionally, the dataset was stratified into urban and rural site classifications to explore the impact of local outdoor emission sources. Urban environments, characterized by higher vehicular traffic and industrial activity, are known to contribute significantly to outdoor VOC levels, which may infiltrate indoor spaces. In contrast, rural sites generally experience lower levels of traffic-related emissions but may have other sources, such as agricultural activities. Urban-rural classification was determined based on the population density of the zip code where each facility was located.

To identify the most representative factor solution, a range of models with three to seven factor solutions was evaluated. The optimal number of factors was selected by assessing scree plots generated from PCA, goodness-of-fit (Q) values from PMF, and the interpretability of the resulting source profiles. Additionally, each factor solution was subjected to 100 bootstrapping runs, ensuring statistical robustness, with a minimum r^2 threshold of 0.6 to confirm the reliability of the identified factors.

Data quality handling 4.4.2

The following table (Table 1) reports the method detection limit, or limit of detection (LOD), for each analyte sampled. Values presented were utilized by the CSU Atmospheric Science department for analysis of gas samples collected using the SUMMA canisters. These values reported in Table 1 also served to inform the uncertainty matrix used within the protocol for PMF, as described previously.

Table 1: Species Limits of Detection

No.	Species	LOD	Unit	No.	Species	LOD	Unit
1	ethane	0.0102	ppbv	31	3-methylheptane	0.0024	ppbv
2	ethene	0.0060	ppbv	32	n-octane	0.0032	ppbv
3	propane	0.0110	ppbv	33	ethylbenzene	0.0022	ppbv
4	propene	0.0044	ppbv	34	m+p-xylene	0.0054	ppbv
5	i-butane	0.0038	ppbv	35	styrene	0.0002	ppbv
6	n-butane	0.0057	ppbv	36	o-xylene	0.0060	ppbv
7	ethyne	0.0051	ppbv	37	n-nonane	0.0058	ppbv
8	t-2-butene	0.0015	ppbv	38	isopropylbenzene	0.0001	ppbv
9	1-butene	0.0042	ppbv	39	n-propylbenzene	0.0003	ppbv
10	c-2-butene	0.0030	ppbv	40	3-ethyltoluene	0.0003	ppbv
11	cyclopentane	0.0026	ppbv	41	4-ethyltoluene	0.0003	ppbv
12	i-pentane	0.0044	ppbv	42	1,3,5-trimethylbenzene	0.0004	ppbv
13	n-pentane	0.0014	ppbv	43	2-ethyltoluene	0.0005	ppbv
14	t-2-pentene	0.0021	ppbv	44	1,2,4-trimethylbenzene	0.0006	ppbv
15	1-pentene	0.0022	ppbv	45	n-decane	0.0069	ppbv
16	cis-2-pentene	0.0036	ppbv	46	1,2,3-trimethylbenzene	0.0004	ppbv
17	n-hexane	0.0058	ppbv	47	1,3-diethylbenzene	0.0004	ppbv
18	isoprene	0.0008	ppbv	48	1,4-diethylbenzene	0.0010	ppbv
19	2,4 dimethylpentane	0.0063	ppbv	49	C2HCl3	0.25	pptv
20	n-heptane	0.0045	ppbv	50	C2Cl4	0.02	pptv
21	benzene	0.0042	ppbv	51	acetonitrile	0.222	ppbv
22	cyclohexane	0.0100	ppbv	52	acetaldehyde	0.410	ppbv
23	2,3-dimethylpentane	0.0084	ppbv	53	acetone	0.210	ppbv
24	2-methylhexane	0.0026	ppbv	54	isopropanol	0.233	ppbv
25	3-methylhexane	0.0050	ppbv	55	methylethylketone	0.128	ppbv
26	2,2,4-trimethylpentane	0.0062	ppbv	56	butanol	0.636	ppbv
27	methylcyclohexane	0.0091	ppbv	57	a-pinene	0.043	ppbv
28	2,3,4-trimethylpentane	0.0055	ppbv	58	b-pinene	0.064	ppbv
29	toluene	0.0046	ppbv	59	limonene	0.055	ppbv
30	2-methylheptane	0.0074	ppbv	60	camphene	0.008	ppbv
				61	methane	0.206	ppmv

Site categorization for PMF 4.4.3

While multiple categorical factors were initially considered, kitchen vs. non-kitchen room classification and seasonality were selected for further analysis. This selection was based on existing literature highlighting the influence of building characteristics on indoor air quality, as well as an evaluation of this study's dataset and site-specific characteristics.

During site walk-throughs and sampling, all rooms were assigned unique names and numbers for reference. Room classifications were determined based on their intended function, observed occupancy rates, and input from site representatives when the actual usage differed from the designated function. For kitchens, any room where cooking activities were actively occurring was classified as a kitchen space, while all other rooms were categorized as non-kitchen rooms. This classification was chosen due to extensive literature documenting high VOC emissions associated with cooking activities. In total, the dataset included nine kitchen-specific samples and 75 non-kitchen room samples.

In addition to room categorization, sampling periods were classified by seasonality to account for potential environmental influences on VOC concentrations. The warm season was defined as May 1st to November 15th, while the cool season was defined as November 15th to May 1st, based on first and last frost dates in Colorado and associated weather patterns. Among the 17 sampled sites, nine sites were monitored during the cool season, resulting in 53 total observations, while eight sites were sampled during the warm season, contributing 31 observations. This classification allowed for an evaluation of seasonal variations in VOC levels, particularly in relation to temperature-driven volatilization and external events such as wildfire activity, which are known to impact air quality during the warmer months.

PMF Sensitivity analyses 4.4.4

To ensure the most representative Positive Matrix Factorization (PMF) model, a comprehensive sensitivity analysis was conducted. A minimum of five different factor solutions were tested, including solutions both above and below the number of factors recommended by Principal Component Analysis (PCA). For example, if PCA suggested a 5-factor solution, additional PMF runs were performed for 3, 4, 6, and 7 factors to evaluate model robustness.

Model performance was assessed based on several key indicators, including:

- Qrobust, Qtrue, and Qexpected (Qexp) values, which provide statistical measures of model fit.
- Convergence rates, where only models achieving 100% convergence were considered valid, as incomplete convergence indicates a poor-fitting model.
- Qtrue/Qexp ratios, which were examined to further validate model selection.
- Bootstrapping analysis, where each factor solution was tested across 100 bootstrapping runs to evaluate factor stability and reproducibility.

Bootstrapping was used as a primary validation tool alongside PCA, as it provides a robust assessment of factor solution stability. During bootstrapping, a factor mapping table is generated, displaying the relationships between the bootstrapped factors and the selected model factors. For example, if a 7-factor solution was selected, the output consisted of a 7×7 matrix, with an additional column representing unmapped species. The optimal solution would show 100% alignment along the diagonal of the table, indicating that each factor was consistently identified across bootstrapped runs, with zero unmapped species.

When comparing multiple factor solutions, the final selected solution was the one that exhibited:

- The highest values along the diagonal, indicating factor stability.
- The lowest number of unmapped species, ensuring that all significant contributors to indoor VOC concentrations were adequately captured.

This rigorous approach ensured that the final PMF model produced the most reliable and interpretable source apportionment of VOCs, minimizing uncertainty and maximizing the robustness of factor assignment.

5. RESULTS

Descriptive Statistics 5.1

Building characterization 5.1.1

In this study, a wide range of building types were monitored for indoor air quality. Among the 50 sites in the study, 18 of the sites also included SUMMA Canister deployments, which were utilized to gather more in-depth data regarding sources of volatile organic compounds in the sample areas. The 18 sites where SUMMA canisters were deployed, ranged across five municipalities including Fort Collins, Denver, Grand Junction, Alamosa, and Rocky Ford. The 18 sites consisted of six community centers/day programming buildings, four assisted living facilities, four shelters for the unhoused, two health care facilities, one child daycare, and one detention center. At each site, there are sample locations with office spaces, dining, living, recreation, health care, sleeping and food preparation areas. Pending facility size and activity levels, three to five SUMMA canisters were placed in sample locations listed above, amounting to 84 total rooms sampled via SUMMA canisters amongst the 18 sites.

VOC analyte concentration summaries 5.1.2

Among indoor samples, the top ten species to contribute to concentrations samples included isopropanol, ethane, propane, acetone, n-butane, i-butane, acetaldehyde, ethene, i-pentane, and n-pentane. The following figure (Figure 4) depicts the observed concentrations of the top ten indoor species present across all sites.

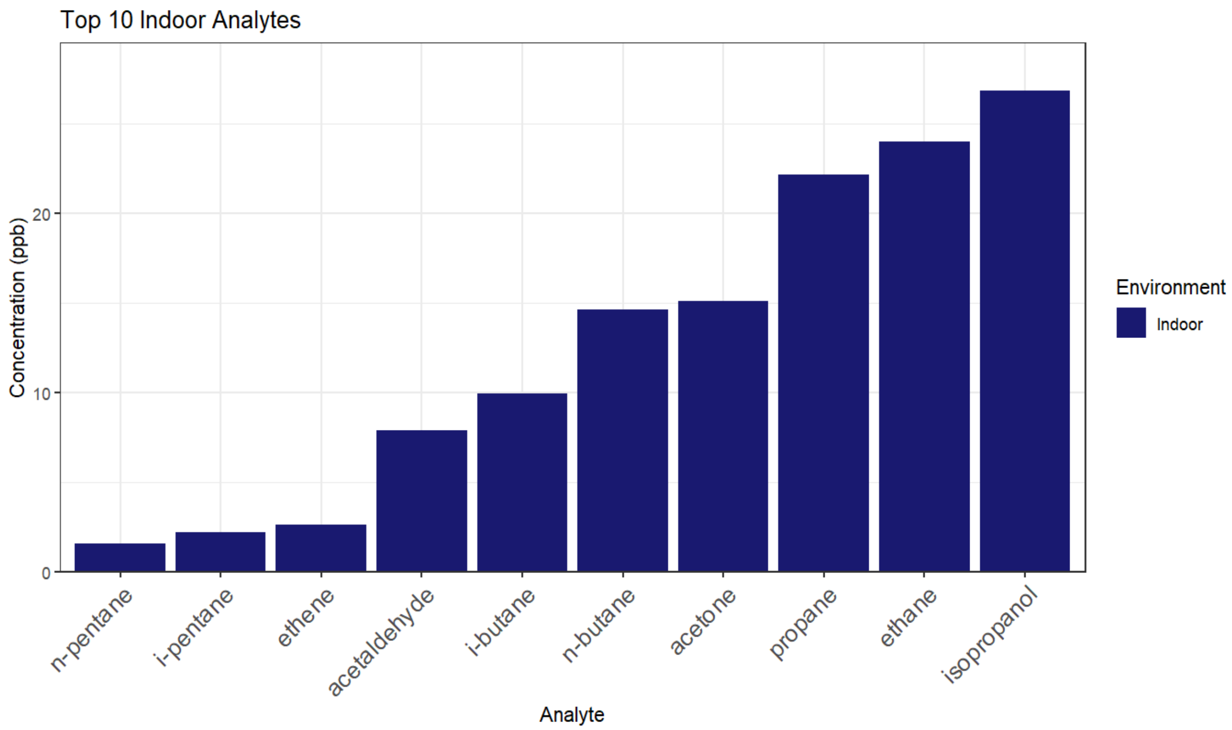

Figure 4: Top 10 Indoor Species Concentrations using Geometric Mean

From outdoor samples, the top ten species contributing to concentrations included ethane, propane, acetone, acetaldehyde, n-butane, ethene, isopropanol, i-pentane, ethyne, and i-butane. Between indoors and outdoors, there was significant overlap in prominent species. With 90% of outdoor top ten species to also be included on the indoor top ten analytes.

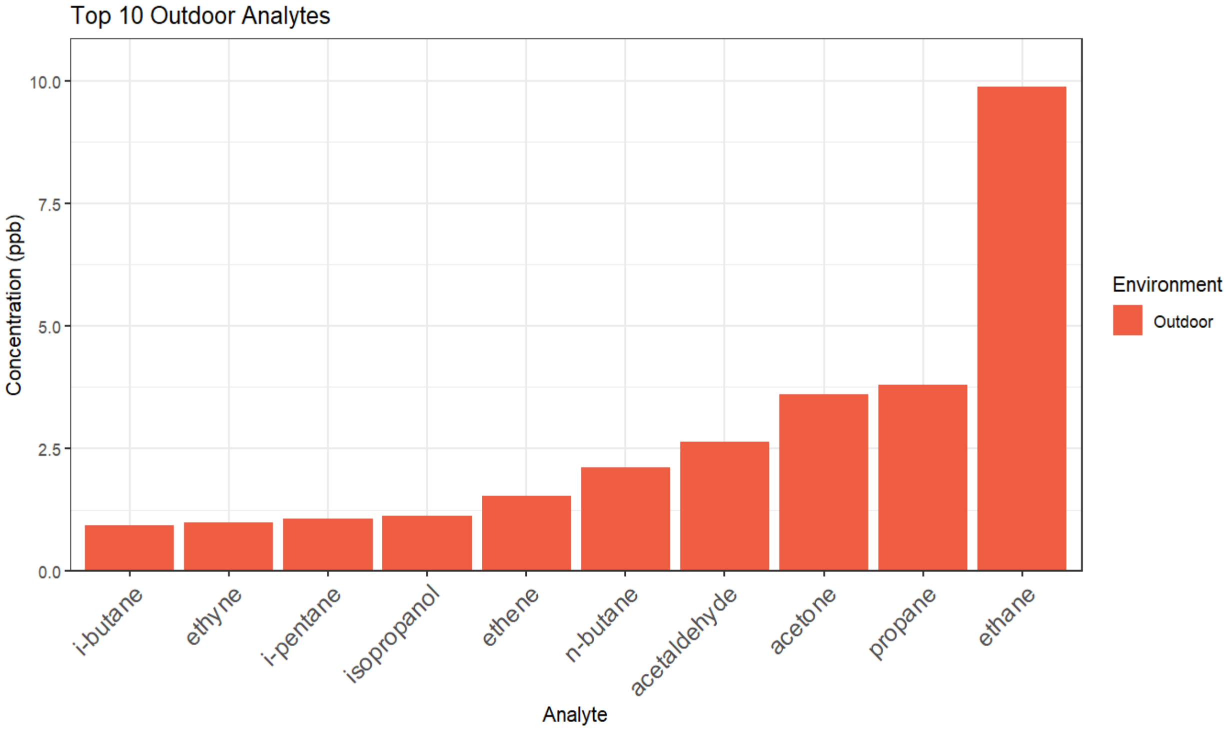

Figure 5: Top 10 Outdoor Species Concentrations using Geometric Mean

With significant overlap between top ten species contributing to indoor and outdoor concentrations, this relationship was plotted in the following figure (Figure 6). The following figure (Figure 6) suggests that i-pentane, ethene, i-butane, acetaldehyde, n-butane, acetone, propane, isopropanol and ethane were all found to be present on the indoor and outdoor top ten lists, while ethyne and n-pentane were present in one environment top ten and not the other. The plot is arranged in ascending order from left to right for indoor environments, while the outdoor concentrations vary to align with the indoor species order.

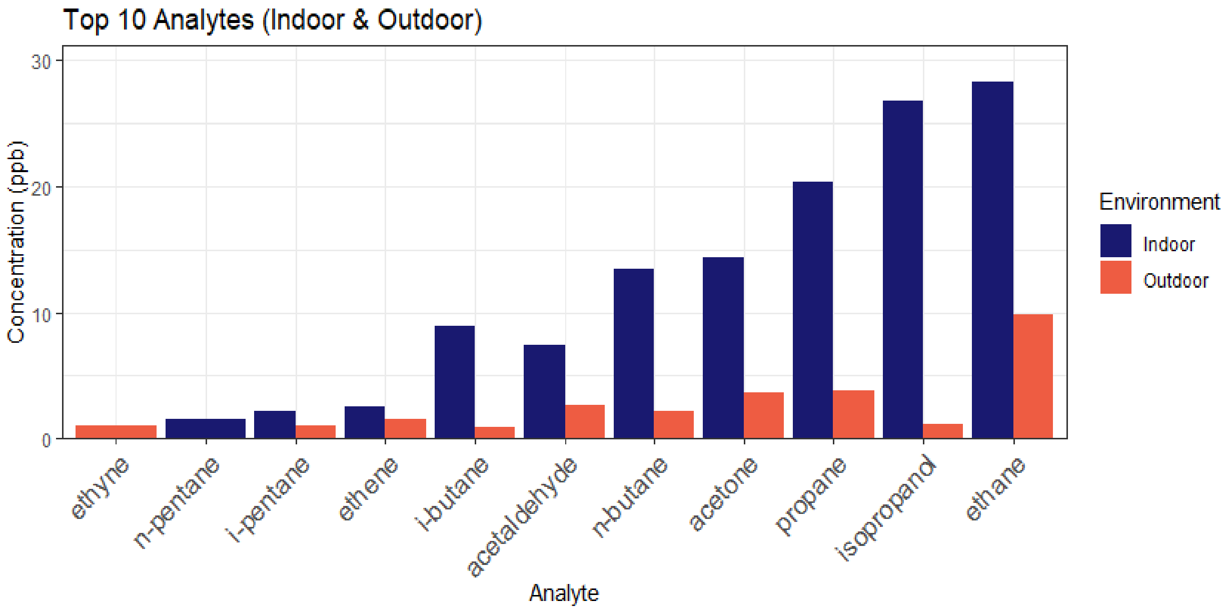

Figure 6: Top 10 Species Concentrations across Indoor and Outdoor Environments

Looking to site and room specific samples, the top 10 indoor species concentrations recorded were attributed to a range of room types, including kitchens, lobbies, offices, lounges, and barracks. Among the top ten concentration samples, ethane accounted for 80% with acetone and isopropanol each appearing once in the top ten samples. Among the top ten outdoor concentrations recorded, ethane also comprised many of these samples, at 60% of the ten samples being attributed to ethane. Propane, i-butane, ethene and isopropanol each appeared once, accounting for 10% respectively of top ten outdoor concentrations sampled.

The following figures (Figure 7 & 8) details the VOC concentrations sampled across all indoor locations and all outdoor locations. It should be noted that the indoor samples include higher recorded concentrations than what was observed in outdoor environments.

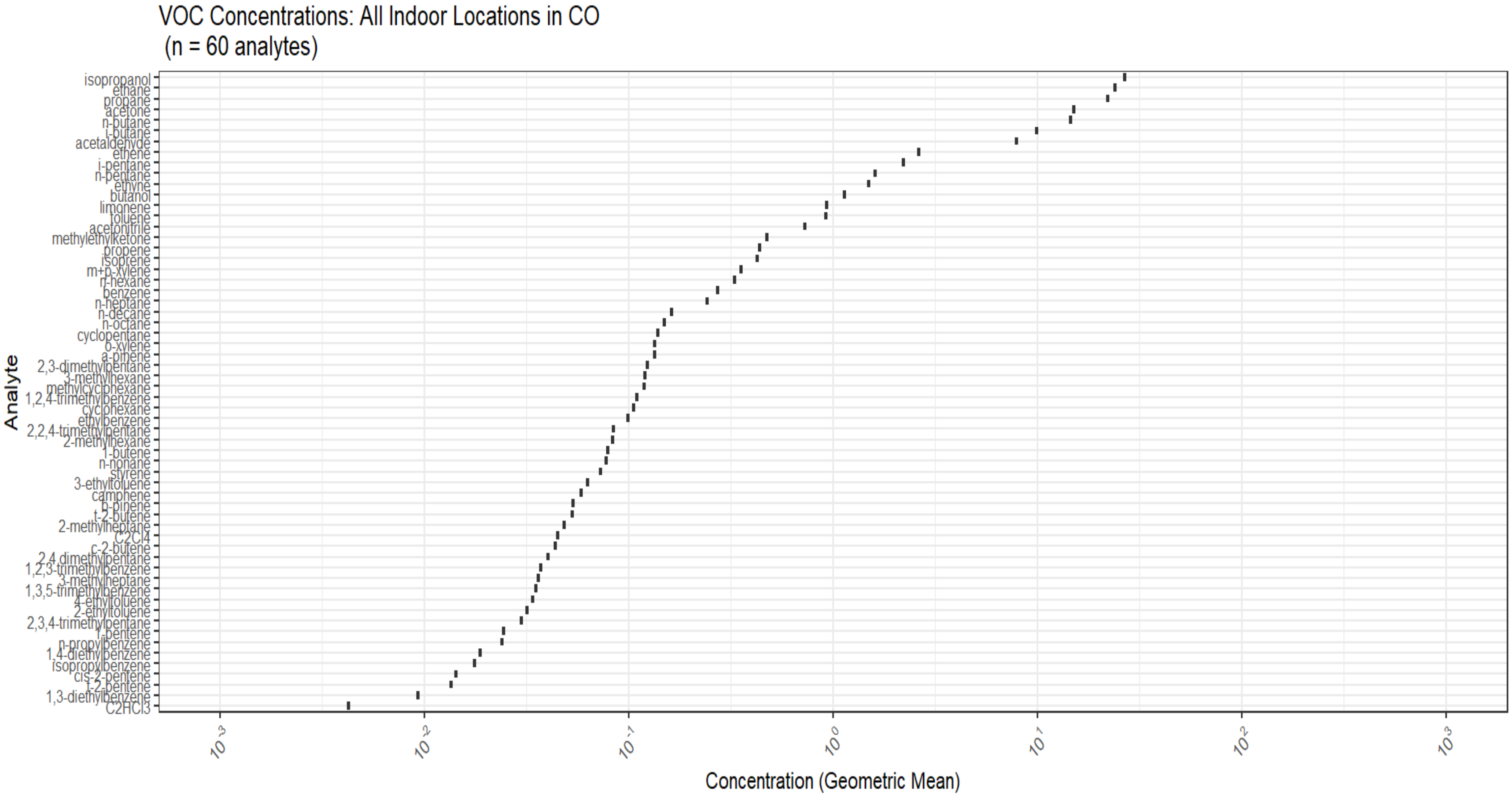

Figure 7: VOC Concentrations across all indoor locations

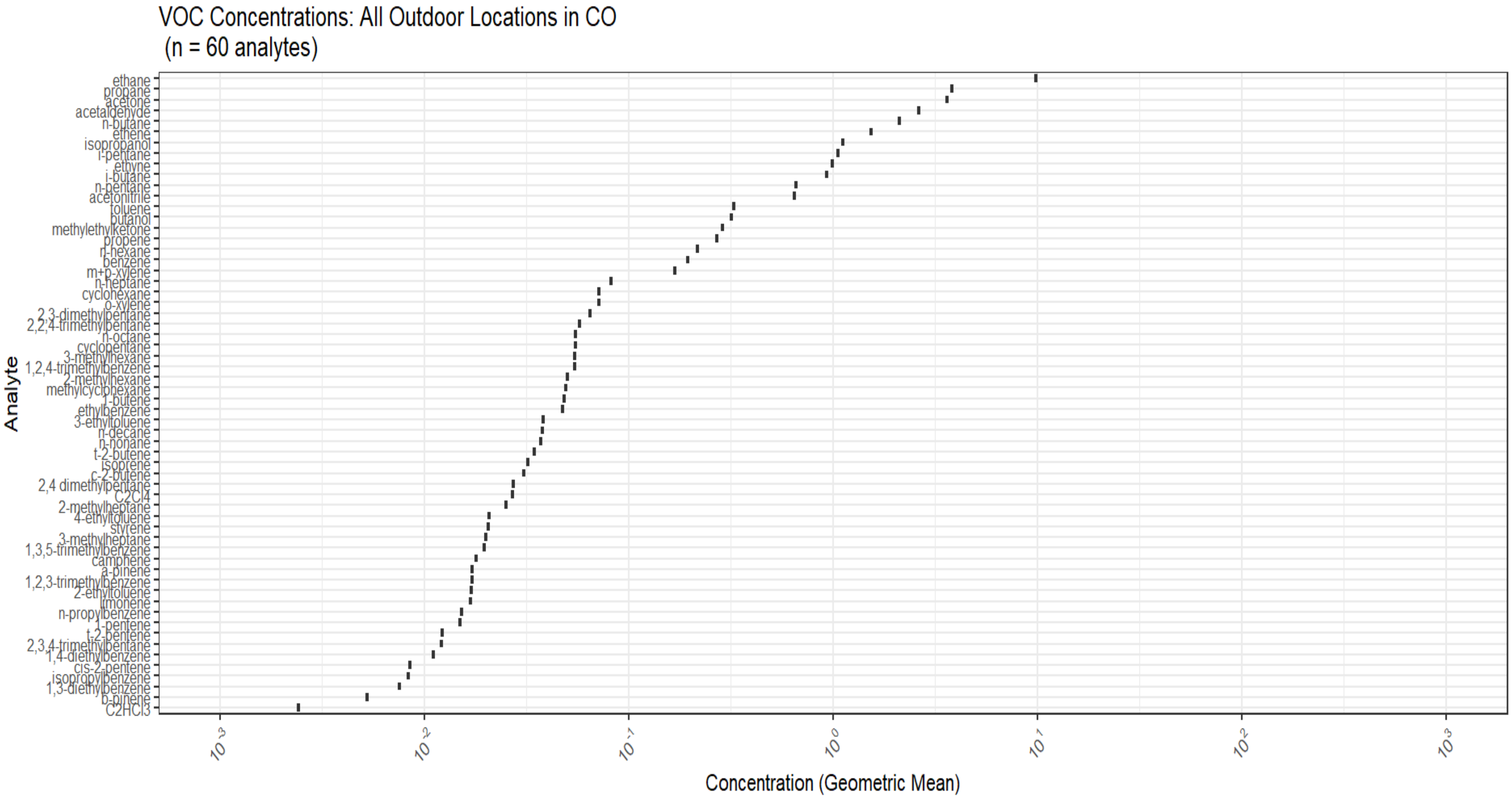

Figure 8: VOC Concentrations across all outdoor locations

Indoor-outdoor VOC ratios 5.1.3

Indoor-to-outdoor (I/O) VOC concentration ratios were calculated to assess the relative contribution of indoor and outdoor sources to overall air quality. These ratios help determine whether specific VOCs originate primarily from indoor sources or if outdoor infiltration significantly influences indoor concentrations.

An I/O ratio close to 1.0 indicates that a given VOC is present in similar concentrations both indoors and outdoors, suggesting balanced contributions from both environments. Ratios below 1.0 suggest that a VOC is more prevalent outdoors than indoors, implying that its presence indoors is largely due to outdoor air infiltration. Conversely, ratios greater than 1.0 indicate that indoor concentrations exceed outdoor levels, suggesting that indoor sources—such as building materials, office equipment, or occupant activities—are the dominant contributors for that particular analyte.[28]

The following figure (Figure 9) depicts the Indoor/Outdoor (I/O) ratios from the data, with the solid blue line at the 1.0 ratio mark, where indoor and outdoor mixing is occurring at an even rate. The data displays that one only species, acetonitrile, was below the 1.0 ratio mark with a ratio of .967. All other species exceeded one, with 80% of species indoor concentrations being one to five times higher than their outdoor concentrations. While 18% of species measured recorded indoor concentrations 6-20 times higher than their outdoor concentrations. Analytes ranging from 6.33-19.78-fold increase over outdoor concentrations include acetone, styrene, limonene, a-pinene, n-butane, i-butane, isoprene, b-pinene, isopropanol and n-decane. Species

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[28] M. de Blas, M. Navazo, L. Alonso, N. Durana, M. C. Gomez, and J. Iza, "Simultaneous indoor and outdoor on-line hourly monitoring of atmospheric volatile organic compounds in an urban building. The role of inside and outside sources," *Science of The Total Environment*, vol. 426, pp. 327–335, Jun. 2012

listed in this range are the top ten analytes I/O ratios. Among the top ten highest I/O ratios, the functional groups are comprised of five alkenes, three alkanes, one alcohol and one ketone. A list format of all mixing ratios can be found in the appendix (Section 9.1).

Analytes included in the top 18% of I/O ratios, ranging from values of 6-20, primarily included species that are known to have high indoor concentrations. Specifically attributed to personal care products and cosmetics, as well as being present in cleaning products.

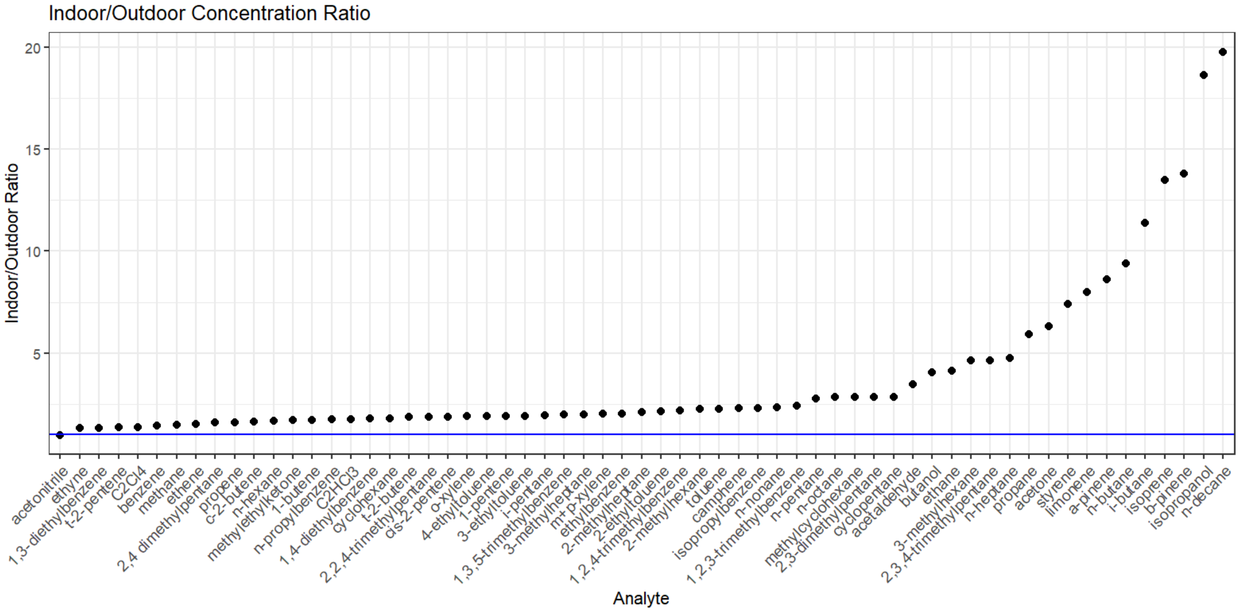

Figure 9: Indoor/Outdoor Ratios

PMF Analysis 5.2

Seasonality 5.2.1

Separate analysis was conducted for sites sampled in warm and cool season periods to evaluate potential differences in source apportionment of VOCs in differing seasons and weather environments. A PCA (principal component analysis) test was conducted for each data set to establish a baseline recommendation for number of appropriate factors for each season. The PCA test suggested five factor solutions for both warm and cool season data. Other factor solutions were also explored utilizing bootstrapping run optimization through the EPA PMF tool. It was determined that increasing or decreasing number of factor solutions beyond 5 solutions saw only negative impacts to the fit of the model.

The following figures (Figures 10 & 11) are the factor fingerprints for warm and cool season 5 factor solutions. The factor fingerprint plots are an output of the EPA PMF tool, and provide a visual interpretation for each species percent contribution to each factor. The percent contributions to each factor are one of the primary guiding observations to the naming of sources attributed to each factor.

When interpreting the factor fingerprint figures, the primary guiding observation comes from distinguishing which species had the largest contribution to the respective factor. For example, below, Factor 3 in green is highly attributed to camphene, b-pinene, limonene, a-pinene and isoprene. Knowing which factors are present, the literature can then be utilized to establish sources that are correlated to the identified species. The literature acts as a guide for defining naming conventions for factors and species being assessed.

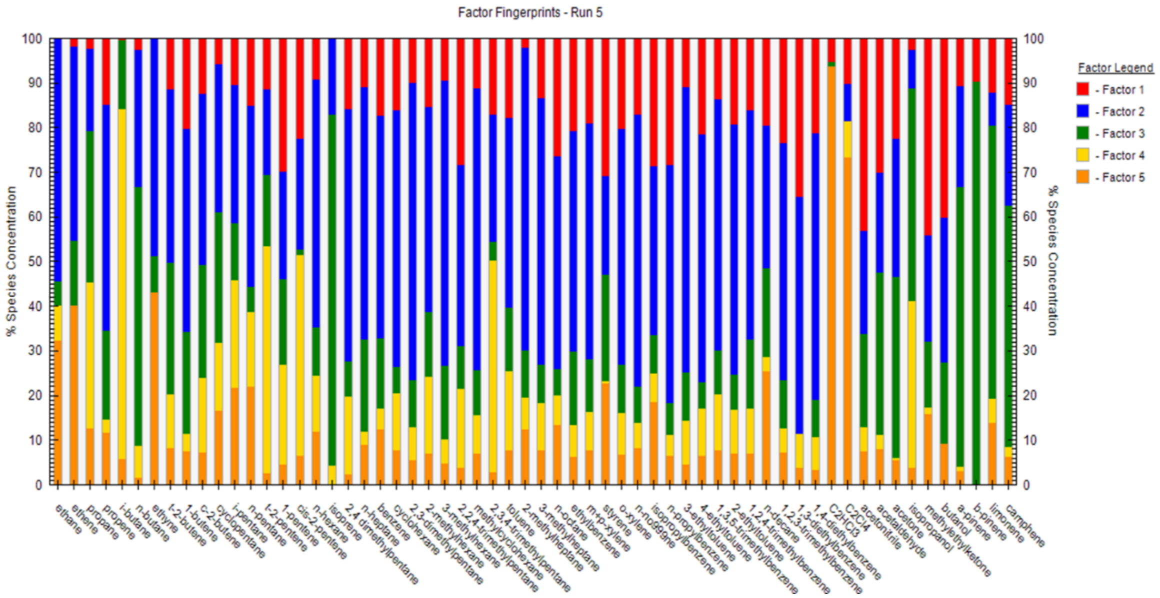

Figure 10: Warm Season Sampling Factor Fingerprint

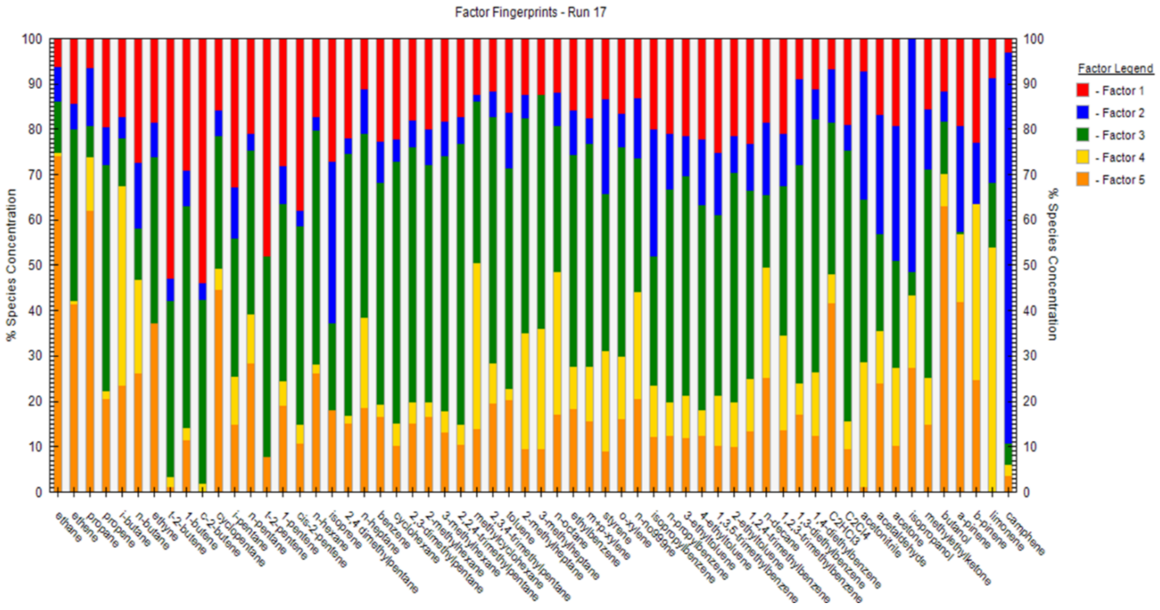

Figure 11: Cool Season Sampling Factor Fingerprint

Warm Season Sampling 5.2.2

Factor 1 was most strongly associated with acetonitrile and methylethylketone, contributing 44.5% and 45.1% of their total mass to this factor. 1-pentane, n-octane and butanol also contributed smaller amounts to Factor 1. The makeup of this factor points to combustions processes and environmental tobacco smoke (ETS).[29] These species can be emitted from different indoor combustion sources such as electric cooking stoves, visitor smoking, candle burning, and barbeques using charcoal or wood as well as outdoor-generated biomass smoke from forest fires.[30]

Factor 2 was comprised mostly of 2,3-dimethylpentane (64.2%), 3-methylhexane (61.5%), 2-methylheptane (61.7%) and 3-ethyltoluene (61.5%). While the prior listed analytes had the highest percent contributions to Factor 2, this factor had the largest number of contributing factors that were the highest percent contribution for the respective analyte. Factor 2 also included BTEX analytes, benzene, toluene, ethylbenzene and xylenes, as well as n-hexane, which points directly to outdoor industrial sources. More specifically, fossil fuel combustion. [31] It is also thought that given the large number of highest contribution analytes to this factor that this may indicate outdoor sources.

Factor 3 leading contributors included n-butane, isoprene, a-pinene, b-pinene, limonene and camphene. Respective percent mass contributions for the listed analytes were measured to be

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[29] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

[30] E. Kabir, K.-H. Kim, J.-W. Ahn, O.-F. Hong, and J. R. Sohn, "Barbecue charcoal combustion as a potential source of aromatic volatile organic compounds and carbonyls," *Journal of Hazardous Materials*, vol. 174, no. 1–3, pp. 492–499, Feb. 2010
V. Y. Seaman, D. H. Bennett, and T. M. Cahill, "Indoor acrolein emission and decay rates resulting from domestic cooking events," *Atmospheric Environment*, vol. 43, no. 39, pp. 6199–6204, Dec. 2009

[31] D. Campagnolo *et al.*, "VOCs and aldehydes source identification in European office buildings - The OFFICAIR study," *Building and Environment*, vol. 115, pp. 18–24, Apr. 2017
H. Pekey, B. Pekey, D. Arslanbaş, Z. B. Bozkurt, G. Doğan, and G. Tuncel, "Source Apportionment of Personal Exposure to Fine Particulate Matter and Volatile Organic Compounds using Positive Matrix Factorization," *Water, Air, & Soil Pollution*, vol. 224, no. 1, Dec. 2012
C. Jia, S. Batterman, and C. Godwin, "VOCs in industrial, urban and suburban neighborhoods—Part 2: Factors affecting indoor and outdoor concentrations," *Atmospheric Environment*, vol. 42, no. 9, pp. 2101–2116, Mar. 2008

57.1%, 77.6%, 62.7%, 89.3%, 60.6% and 54.4%. These species, a-pinene, b-pinene, camphene and limonene, are typically found in consumer products with fragrance, perfumes and essential oils such as air fresheners, deodorizers, laundry detergents, fabric softeners, hand sanitizers, personal care products, baby shampoo, soaps, and cleaning supplies.[32] Given the strong percent contributions to this factor, factor 3 has been determined to represent ozone-initiated oxidation products, which includes n-butane and isoprene. Sources of ozone-initiated oxidation products may include personal care products, as well as adhesives, wood products, fragrances, and building materials.[33]

Factor 4 was most strongly associated with i-butane, which accounted for 75.9% of i-butanes total mass contribution. Isobutane is correlated with fuel oil combustion and evaporated gasoline. Which may include turning on and off gasoline powered items, stored paints, and evaporated gasoline from cooking activities or outdoor processes.[34]

Among warm season samples, Factor 5 was most associated to ethane, ethene, ethyne, $C2HCl3$ and $C2Cl4$. Contributing 33.2, 41.5, 43.7, 93 and 72.5 percent of their total masses to Factor 5. The strong contributions from ethane, ethene and ethyne suggest a relationship to the

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[32] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015
D. Campagnolo *et al.*, "VOCs and aldehydes source identification in European office buildings - The OFFICAIR study," *Building and Environment*, vol. 115, pp. 18–24, Apr. 2017
M. S. Zuraimi, K. W. Tham, and S. C. Sekhar, "A study on the identification and quantification of sources of VOCs in 5 air-conditioned Singapore office buildings," *Building and Environment*, vol. 39, no. 2, pp. 165–177, Feb. 2004

[33] Y. Liu, M. Shao, L. Fu, S. Lu, L. Zeng, and D. Tang, "Source profiles of volatile organic compounds (VOCs) measured in China: Part I," *Atmospheric Environment*, vol. 42, no. 25, pp. 6247–6260, Aug. 2008

[34] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

oil and gas industry.[35] While the strongest contribution, C2HCl3 (TCE) at 80.6% of its total mass attributed to Factor 5 has been detected in the air all throughout the United States. According to ATSDR (1997a), atmospheric levels are highest in areas concentrated with industry and population, and lower in remote and rural regions. Air levels of TCE are highly variable (fluctuate widely over relatively short periods of time), depending on strength of emission sources, variation of wind direction and velocity and other meteorological factors, rain scavenging, and photodecomposition.[36]

The following figure (Figure 12) is the base factor profile for warm season sampling, with the species concentration on the y axis shown via the blue bars, with the percent species contribution to each factor denoted by the red squares on the plots. Similarly to the factor fingerprint figures, the percent of species contribution allows for the interpretation of which species are most distinctively contributing to the source. The base factor profiles provide insight to the makeup of each factor and direction for reviewing the literature for source identification and naming.

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[35] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

[36] "SOURCES, EMISSION AND EXPOSURE FOR TRICHLOROETHYLENE (TCE) AND RELATED CHEMICALS," National Center for Environmental Assessment–Washington Office Office of Research and Development , U.S. Environmental Protection Agency Washington, DC 20460, Mar. 2001.

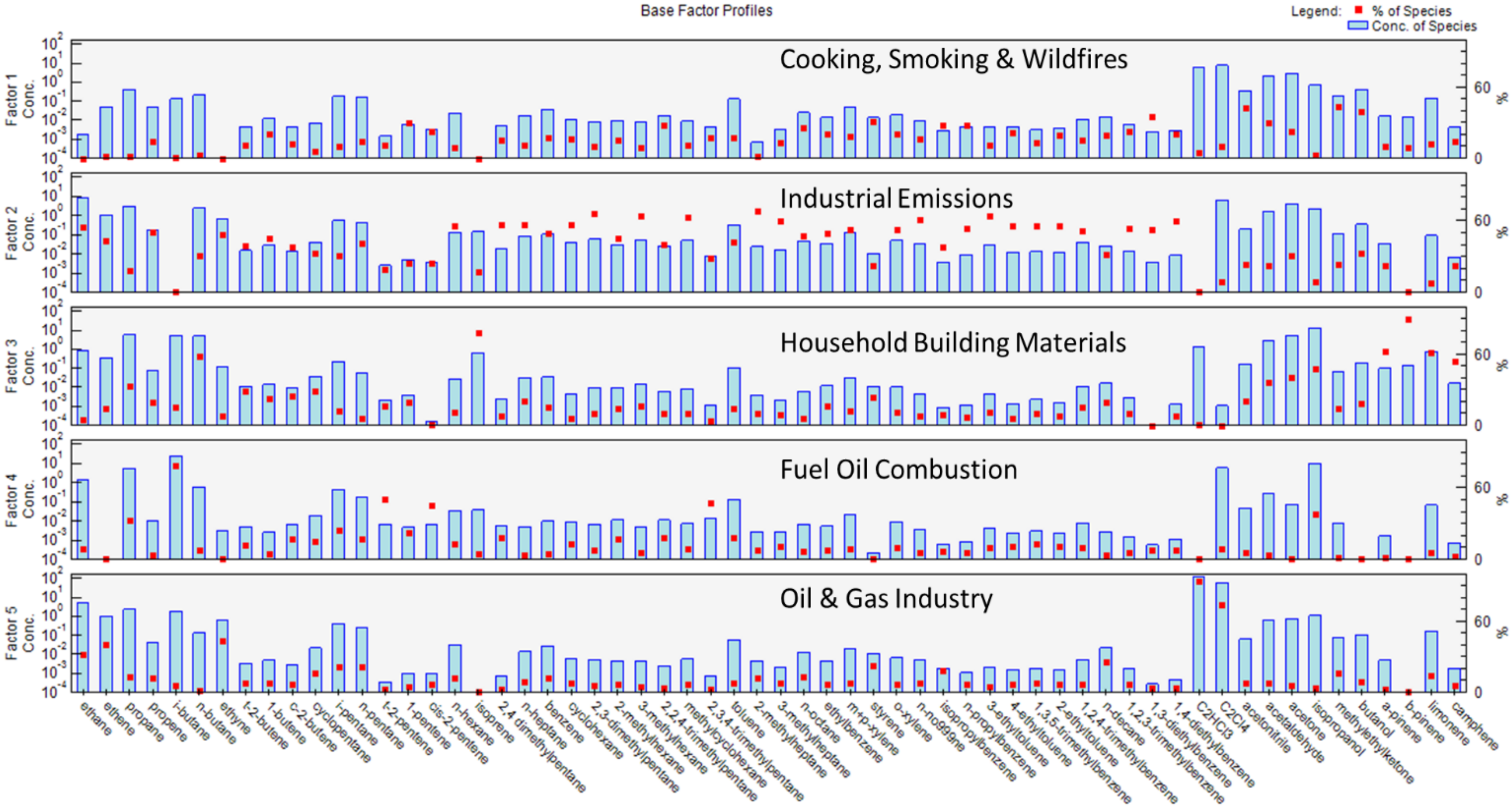

Figure 12: Base Factor Profiles for Warm Season Sampling

Cool Season Sampling 5.2.3

Like Factor 2 in warm season sampling, Factor 1 was comprised of t-2-butene and c-2-butene, contributing 53% and 54% of their total mass to Factor 1. This factor also included contributions from n-butane, i-pentane and t-2-pentene. The Texas Commission on Environmental Quality has determined that cis and trans (-2-butene) is released into ambient air from a variety of sources. Trace levels of butene's can be identified in urban and suburban air arising from combustion of fossil fuels and losses from gas plants and refineries. Cis-2- and trans-2-butene are chemical isomers that are flammable, colorless gases with a "gashouse" odor. They frequently occur together as a mixture and are referred to as 2-butene. Cis-2- and trans-2-butene are used as solvents and cross-linking agents. They are used in the synthesis of or as a chemical intermediate of other chemicals. They are a component of liquefied petroleum gas.[37] The species make up of Factor 1 is correlated to fuel combustion sources, more specifically, petroleum.[38]

The predominant species found in the source profile of Factor 2 for the cool season sampling was isopropanol and camphene, which accounted for 51.6% and 86.25 of their total mass contribution for this factor. Camphene is highly correlated to personal care products [39] and isopropanol is found in many cosmetic products.[40] Factor 2 was determined to be cosmetics and personal care products being the primary source. Factor 2 for warm season sampling was found

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[37] FACT SHEET 2-BUTENE (CIS AND TRANS) CAS #: 107-01-7 CIS-2-BUTENE CAS #: 590-18-1 TRANS-2-BUTENE CAS #: 624-64-6," 2008.

[38] D. E. Saraga *et al.*, "Source apportionment for indoor air pollution: Current challenges and future directions," *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023

[39] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

[40] New Jersey Department of Health, "Right to Know Hazardous Substance Fact Sheet," Feb. 2016.

to be industrial emissions, whereas personal care products and building materials appeared in Factor 3 in warm season sampling.

Comparable to Factor 4 in warm season sampling, Factor 3 was heavily weighted by 2,4 dimethylpentane (57.6%), cyclohexane (57.8%), 2,3-dimethylpentane and 3-methylhexane (56.4), 2,2,4-trimethylpentane (62%) and C2Cl4 (59.9%). Factor 3 was comprised of the largest number of species and included BTEX species as well as n-hexane. The contributing species to this factor suggest a source of industrial emissions from outdoor environments, more specifically, fossil fuel combustion.[41] Comparatively, Factor 3 in warm season sampling was determined to be household building materials, likely from indoor sources.

Factor 4 was strongly attributed to i-butane and limonene, comprised of 44% and 53.85% of their total mass contribution to this factor. This factor was also associated with methylcyclohexane, and b-pinene. Isobutane and limonene are both commonly found in air fresheners and cleaning products, thus was marked as cleaning products being the primary source of species in Factor 4.[42] Factor 4 in warm season sampling was comprised of fuel oil combustion sources.

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[41] D. E. Saraga *et al.*, “Source apportionment for indoor air pollution: Current challenges and future directions,” *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023
D. Campagnolo *et al.*, “VOCs and aldehydes source identification in European office buildings - The OFFICAIR study,” *Building and Environment*, vol. 115, pp. 18–24, Apr. 2017
H. Pekey, B. Pekey, D. Arslanbaş, Z. B. Bozkurt, G. Doğan, and G. Tuncel, “Source Apportionment of Personal Exposure to Fine Particulate Matter and Volatile Organic Compounds using Positive Matrix Factorization,” *Water, Air, & Soil Pollution*, vol. 224, no. 1, Dec. 2012
C. Jia, S. Batterman, and C. Godwin, “VOCs in industrial, urban and suburban neighborhoods—Part 2: Factors affecting indoor and outdoor concentrations,” *Atmospheric Environment*, vol. 42, no. 9, pp. 2101–2116, Mar. 2008

[42] N. B. Goodman, A. J. Wheeler, P. J. Paevere, P. W. Selleck, M. Cheng, and A. Steinemann, “Indoor volatile organic compounds at an Australian university,” *Building and Environment*, vol. 135, pp. 344–351, May 2018

Factor 5 was highly enriched by ethane, propane and butanol (74.2%, 62.1% and 63.1% respectively), and also included ethene, ethyne, cyclopentane and n-decane as contribution species. Given the inclusion of tracer species, it was determined that the source of Factor 5 is broadly the oil and gas industry.[43] In warm season sampling, the oil & gas industry source was most correlated to Factor 5 as well.

The following figure (Figure 13) is the base factor profile for cool season sampling, with the species concentration on the y axis shown via the blue bars, with the percent species contribution to each factor denoted by the red squares on the plots.

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[43] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

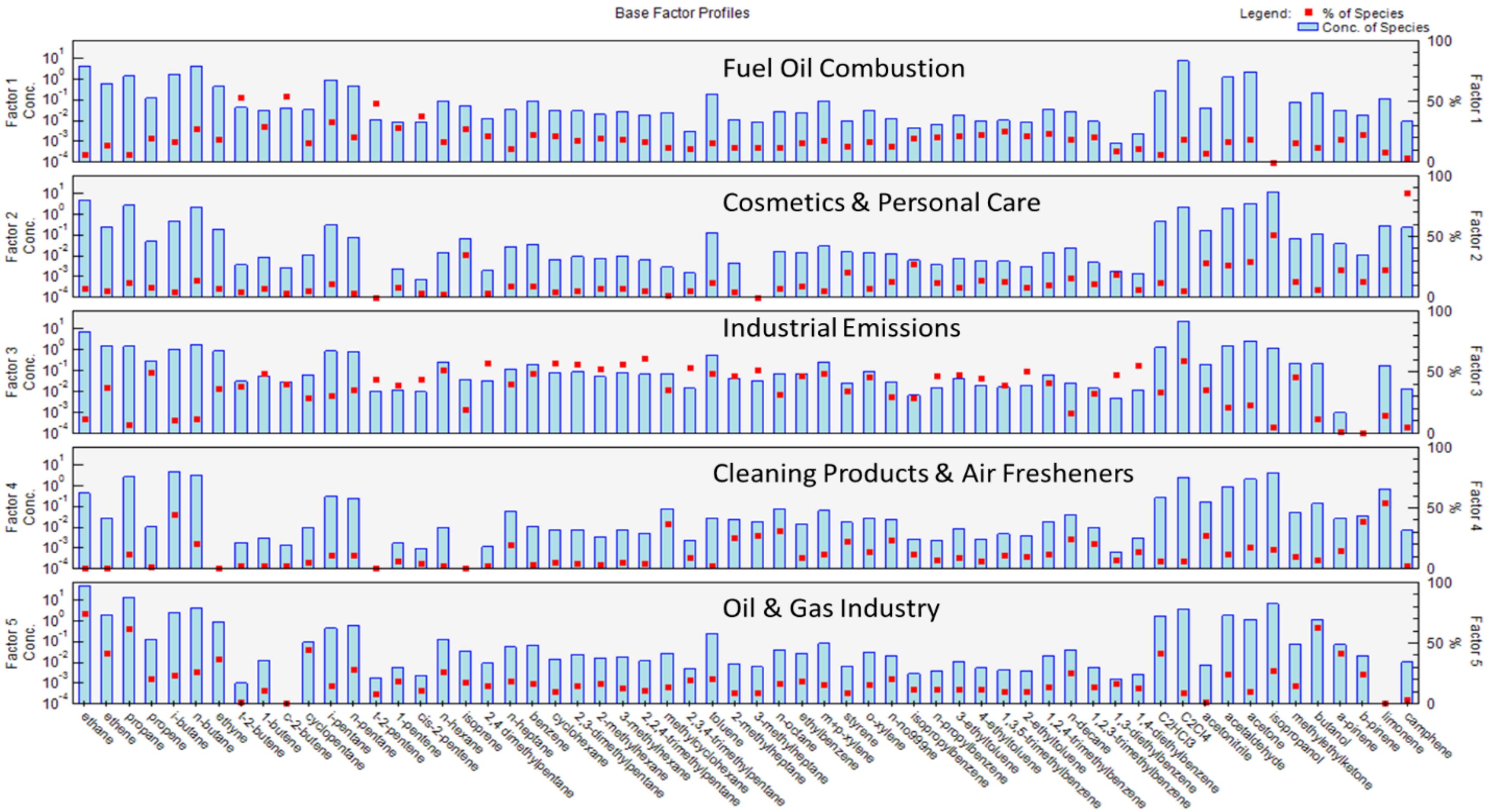

Figure 13: Base Factor Profiles for Cool Season Sampling

Kitchen Based Source Apportionment 5.2.4

In addition to warm and cool season source apportionment testing, the SUMMA canister data were also evaluated in subsets based on sampling location; namely, kitchen and non-kitchen rooms. This designation was conducted based on prior understanding that increased levels of VOCs are known to be prevalent in kitchen spaces.[44] Kitchens and cafeteria room types were included in the kitchens only solution, and all other room types where SUMMA canisters were placed are denoted as non-kitchen rooms. A PCA (principal component analysis) test was conducted for each data set to establish a baseline recommendation for number of appropriate factors for each season. The PCA test suggested 5 factor solutions for both warm and cool season data. Other factor solutions were also explored utilizing bootstrapping run optimization through the EPA PMF tool. It was determined that increasing or decreasing number of factor solutions beyond 5 solutions saw only negative impacts to the fit of the model.

The following figures (Figures 14 & 15) are the factor fingerprints for kitchen and non-kitchen rooms five factor solutions. The factor fingerprint plots are an output of the EPA PMF tool and provide a visual interpretation for each species percent contribution to each factor. The percent contributions to each factor are one of the primary guiding observations to the naming of sources attributed to each factor.

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[44] C. Alves *et al.*, “Fine Particulate Matter and Gaseous Compounds in Kitchens and Outdoor Air of Different Dwellings,” *International Journal of Environmental Research and Public Health*, vol. 17, no. 14, p. 5256, Jul. 2020

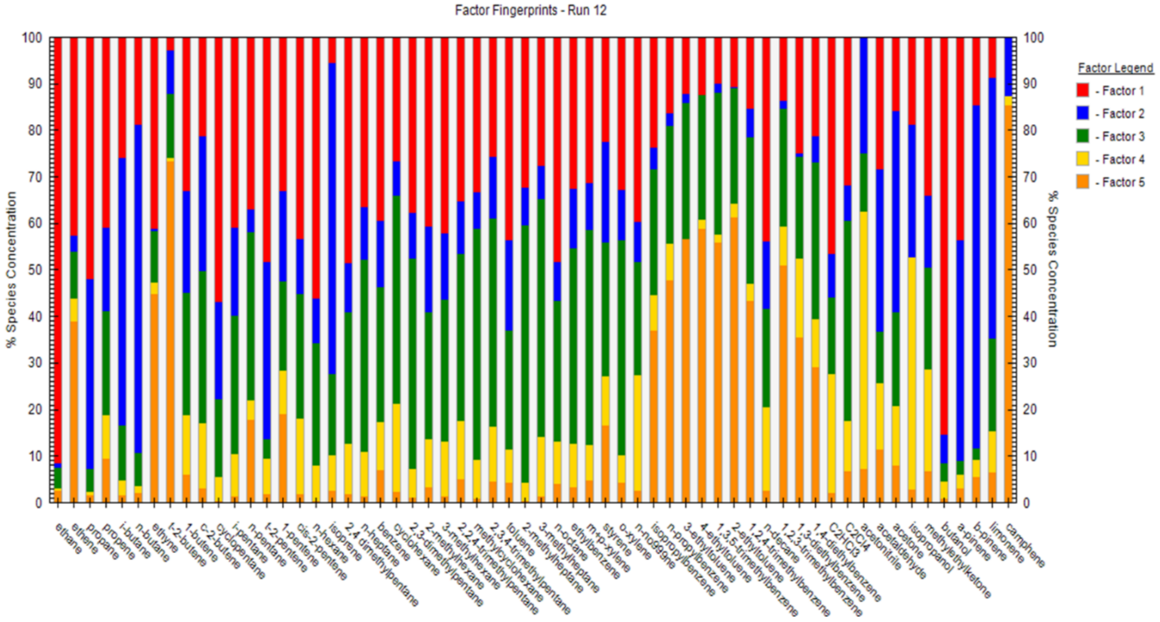

Figure 14: Kitchens Only Sampling Base Factor Profiles

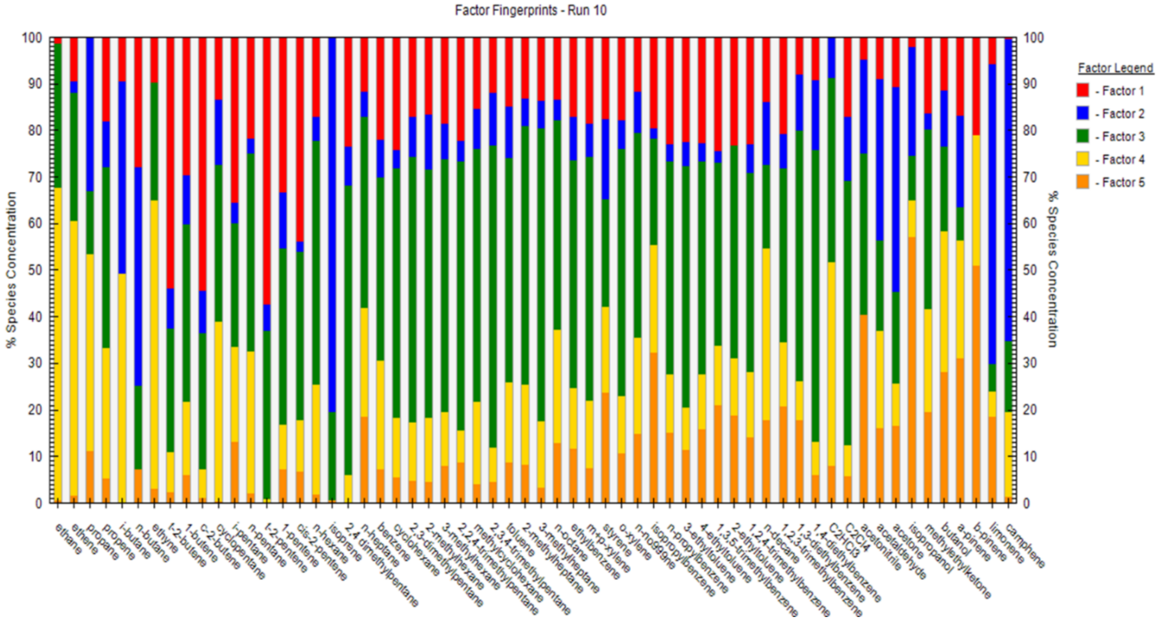

Figure 15: Non-Kitchen Sampling Base Factor Profiles

Kitchens Only Sampling 5.2.5

Factor 1 of the 5-factor solution was primarily attributed to ethane and butanol, which accounted for 91.2% and 85.5% mass contribution to Factor 1. These species, while they hold the highest percent contribution status, were accompanied by cyclopentane (55.9%), n-hexane (55.7%), C2HCl3 (53%). Ethane is most associated with oil and gas, being one of the most significant sources for ethane.[45] With butanol also being associated to fuel combustion.[46] Ethane and butanol had I/O ratios of 4.13 and 4.07, respectively, which indicates that sources of ethane and butanol were four times higher indoors than outdoors. Suggesting that Factor 1 is attributed to the indoor combustion of fuels.

Factor 2 was comprised of i-butane, n-butane, isoprene and b-pinene, being the largest contributing species to the factor. Percent contributions to this factor for the listed species are 61.1%, 72.6%, 71.2%, and 78% respectively. Other analytes that made up this factor include acetone, a-pinene and limonene. Species included suggest ozone-initiated oxidation products. Which may include personal care products, adhesives, and fragrances.[47] The source contributing to Factor 2 has been defined as fragranced household cleaning products.

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[45] D. E. Saraga *et al.*, “Source apportionment for indoor air pollution: Current challenges and future directions,” *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023
J.-H. Tsai, V. How, W.-C. Wang, and H.-L. Chiang, “Characteristics of Airborne Pollutants in the Area of an Agricultural–Industrial Complex near a Petrochemical Industry Facility,” *Atmosphere*, vol. 14, no. 5, pp. 803–803, Apr. 2023

[46] PubChem, “1-Butanol,” *Nih.gov*, 2025 (accessed Feb. 19, 2025).

[47] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, “Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada,” *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015
D. Campagnolo *et al.*, “VOCs and aldehydes source identification in European office buildings - The OFFICAIR study,” *Building and Environment*, vol. 115, pp. 18–24, Apr. 2017
M. S. Zuraimi, K. W. Tham, and S. C. Sekhar, “A study on the identification and quantification of sources of VOCs in 5 air-conditioned Singapore office buildings,” *Building and Environment*, vol. 39, no. 2, pp. 165–177, Feb. 2004

Factor 3 was strongly associated with n-heptane, 2,3-dimethylpentane, 2,2,4-trimethylpentane, and 2-methylheptane with 42.7%, 47.2.2%, 43% and 55% mass contribution of each species respectively. Factor 3 was also associated with c-2-butene, t-2-pentene and other alkanes, at lower percent contributions. These species have been shown to be highly enriched in evaporated gasoline in several studies.[48] Additionally, trace levels of butene's can be identified in urban and suburban air arising from combustion of fossil fuels and losses from gas plants and refineries.[49] Suggesting that the primary source contributing to Factor 3 is outdoor fuel combustion.[50]

Factor 4 was defined by acetonitrile, 43.1%, which was one of the only analytes that its largest percent mass composition was attributed to Factor 4. Acetonitrile is most associated with environmental tobacco smoke (ETS).[51] There was also a strong contribution from isopropanol, of roughly 44%. Given the contributing species, factor 4 has been determined to be contributed to vehicular exhaust and smoke.

Y. Liu, M. Shao, L. Fu, S. Lu, L. Zeng, and D. Tang, "Source profiles of volatile organic compounds (VOCs) measured in China: Part I," *Atmospheric Environment*, vol. 42, no. 25, pp. 6247–6260, Aug. 2008

New Jersey Department of Health, "Right to Know Hazardous Substance Fact Sheet," Feb. 2016.

[48] K. Na, Y. P. Kim, I. Moon, and K.-C. Moon, "Chemical composition of major VOC emission sources in the Seoul atmosphere," *Chemosphere*, vol. 55, no. 4, pp. 585–594, Apr. 2004

J. G. Watson, J. C. Chow, and E. M. Fujita, "Review of volatile organic compound source apportionment by chemical mass balance," *Atmospheric Environment*, vol. 35, no. 9, pp. 1567–1584, Mar. 2001

[49] FACT SHEET 2-BUTENE (CIS AND TRANS) CAS #: 107-01-7 CIS-2-BUTENE CAS #: 590-18-1 TRANS-2-BUTENE CAS #: 624-64-6," 2008.

[50] D. E. Saraga *et al.*, "Source apportionment for indoor air pollution: Current challenges and future directions," *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023.

[51] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015.

Factor 5 was dominated by t-butene, 3-ethyltoluene, 4-ethyltoluene, 1,3,5-trimethylbenzene and 2-ethyltoluene. Respectively, with 74.6%, 62.8%, 59.5%, 61.2% and 63.6% mass contribution to Factor 5 for each of the species. Factor 5 was mostly attributed to camphene, with an 85.2% contribution. Other species present in Factor 5 primarily consisted of arenes. An indoor air pollution source apportionment study conducted by D. E. Saraga *et al*. found that many of the species attributed to Factor 5 were most prevalent in flooring emissions. Given the combination of contributing analytes to this factor, Factor 5 has been determined to be sourced by building and flooring materials.

The following figure (Figure 16) is the base factor profile for kitchen only sampling, with the species concentration on the y axis shown via the blue bars, with the percent species contribution to each factor denoted by the red squares on the plots.

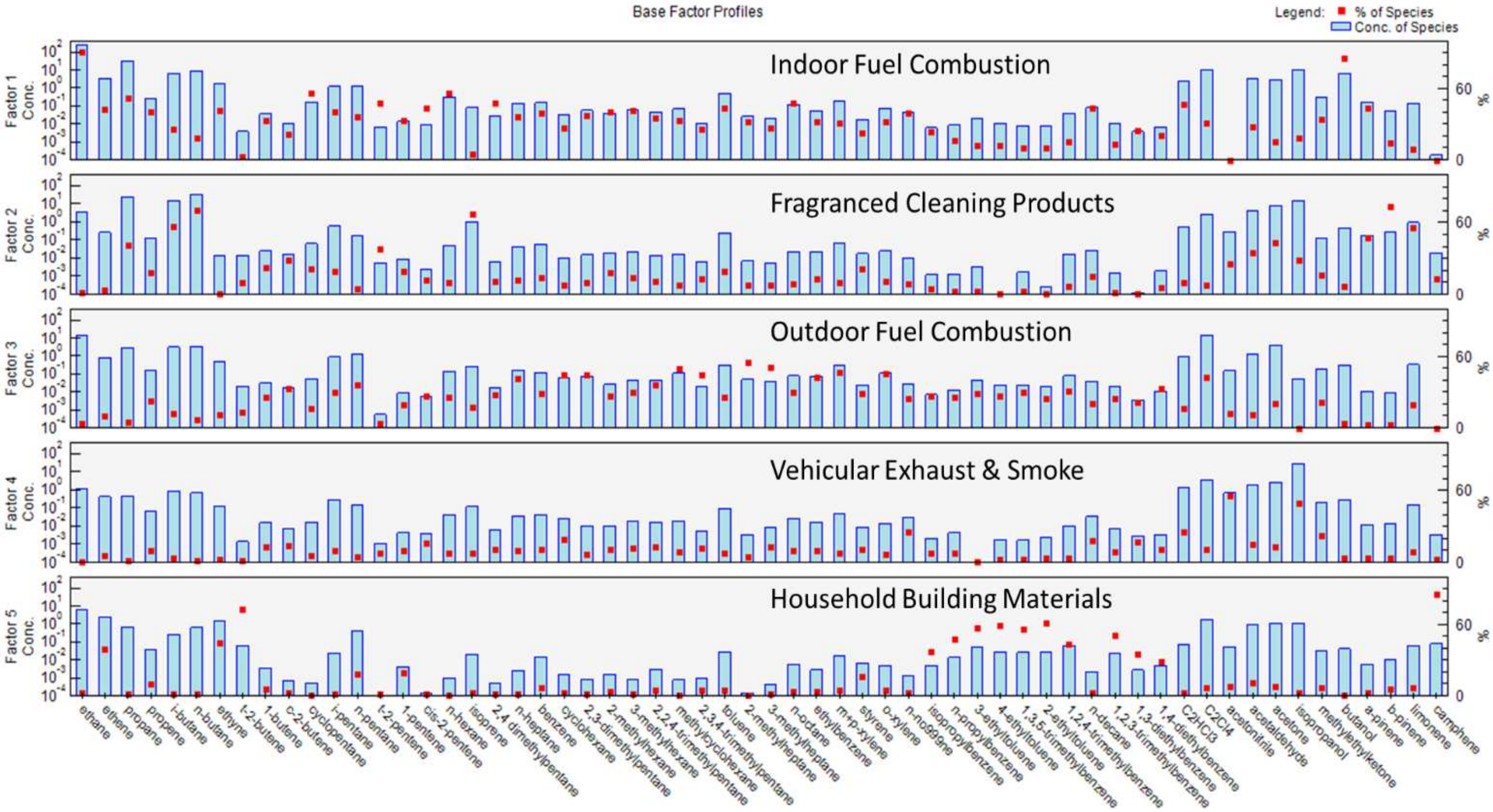

Figure 16: Kitchens Only Sampling Base Factor Profiles

Non-Kitchens Room Sampling 5.2.6

Factor 1 was defined by the presence of t-2-butene, c-2-butene and t-2-pentene, with percent contributions being 53.8%, 54.5% and 57.5% respectively. Species also present included 1-butene, i-pentane and cis-2-pentene. These species have been shown to be highly enriched in evaporated gasoline in several studies.[52] Additionally, trace levels of butene's can be identified in urban and suburban air arising from combustion of fossil fuels and losses from gas plants and refineries.[53] The make-up of analytes in this factor suggests fuel oil combustion as being the primary source for Factor 1.

Factor 2 was defined by isoprene, contributing 80.6% of its mass composition to factor 2. Limonene and camphene were also present, contributing 64.4% and 65.9% respectively to Factor 2. Camphene is highly correlated to personal care products [54] and isoprene is found in many cosmetic products.[55] Based on the present analytes, Factor 2 has been defined as cosmetics and personal care products.

Factor 3 was composed of 2,4-dimethylpentane, 2,3,4 trimethylpentane, 3 methylheptane, C2Cl4 and 1,4-diethylbenzene. Percent contributions for the species listed were found to be 62%, 65%, 62.8%, 56% and 62.5% respectively. This factor included the greatest number of species that had the highest percent contribution to this source and included BTEX species as well as n-

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[52] K. Na, Y. P. Kim, I. Moon, and K.-C. Moon, "Chemical composition of major VOC emission sources in the Seoul atmosphere," *Chemosphere*, vol. 55, no. 4, pp. 585–594, Apr. 2004
J. G. Watson, J. C. Chow, and E. M. Fujita, "Review of volatile organic compound source apportionment by chemical mass balance," *Atmospheric Environment*, vol. 35, no. 9, pp. 1567–1584, Mar. 2001

[53] FACT SHEET 2-BUTENE (CIS AND TRANS) CAS #: 107-01-7 CIS-2-BUTENE CAS #: 590-18-1 TRANS-2-BUTENE CAS #: 624-64-6," 2008. Available: f

[54] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, "Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada," *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

[55] New Jersey Department of Health, "Right to Know Hazardous Substance Fact Sheet," Feb. 2016.

hexane. Inclusion of these species, and noting the most prominent analytes, Factor 3 has been defined as outdoor fuel combustion being the primary source of VOCs attributed.[56] Factor 3 in the kitchen-based sampling was also attributed to outdoor fuel combustion.

Factor 4 was primarily composed of ethane, ethene and ethyne (67.9%, 58.9% and 62%), which are known to be oil and gas tracer species. Other analytes associated with this factor include propane, propene, i-butane, n-decane and butanol. These species are typically emitted from oil and gas industries (e.g., natural gas extraction and processing, and oil and petrochemical refining).[57] Given the inclusion of species, it was determined that the source of Factor 5 is broadly the oil and gas industry.[58]

Amongst indoor samples that do not include kitchens, Factor 5 was attributed to 57.2% mass contribution from isopropanol and 50.9% mass contribution from b-pinene. Also populating this factor included styrene, isopropyl benzene, acetonitrile and a-pinene. Species included suggest ozone-initiated oxidation products. Which may include personal care products, adhesives, and fragrances.[59] This factor indicates that the primary source is fragranced household cleaning products. Similarly, in kitchen-based sampling, this factor is comparable to Factor 2.

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[56] D. E. Saraga *et al.*, “Source apportionment for indoor air pollution: Current challenges and future directions,” *Science of The Total Environment*, vol. 900, p. 165744, Nov. 2023

[57] J. G. Watson, J. C. Chow, and E. M. Fujita, “Review of volatile organic compound source apportionment by chemical mass balance,” *Atmospheric Environment*, vol. 35, no. 9, pp. 1567–1584, Mar. 2001

[58] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, “Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada,” *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015

[59] Md. A. Bari, W. B. Kindzierski, A. J. Wheeler, M.-È. Héroux, and L. A. Wallace, “Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada,” *Building and Environment*, vol. 90, pp. 114–124, Aug. 2015
D. Campagnolo *et al.*, “VOCs and aldehydes source identification in European office buildings - The OFFICAIR study,” *Building and Environment*, vol. 115, pp. 18–24, Apr. 2017

The following figure (Figure 17) is the base factor profile for non-kitchen room sampling, with the species concentration on the y axis shown via the blue bars, with the percent species contribution to each factor denoted by the red squares on the plots.

M. S. Zuraimi, K. W. Tham, and S. C. Sekhar, “A study on the identification and quantification of sources of VOCs in 5 air-conditioned Singapore office buildings,” *Building and Environment*, vol. 39, no. 2, pp. 165–177, Feb. 2004

Y. Liu, M. Shao, L. Fu, S. Lu, L. Zeng, and D. Tang, “Source profiles of volatile organic compounds (VOCs) measured in China: Part I,” *Atmospheric Environment*, vol. 42, no. 25, pp. 6247–6260, Aug. 2008

New Jersey Department of Health, “Right to Know Hazardous Substance Fact Sheet,” Feb. 2016.

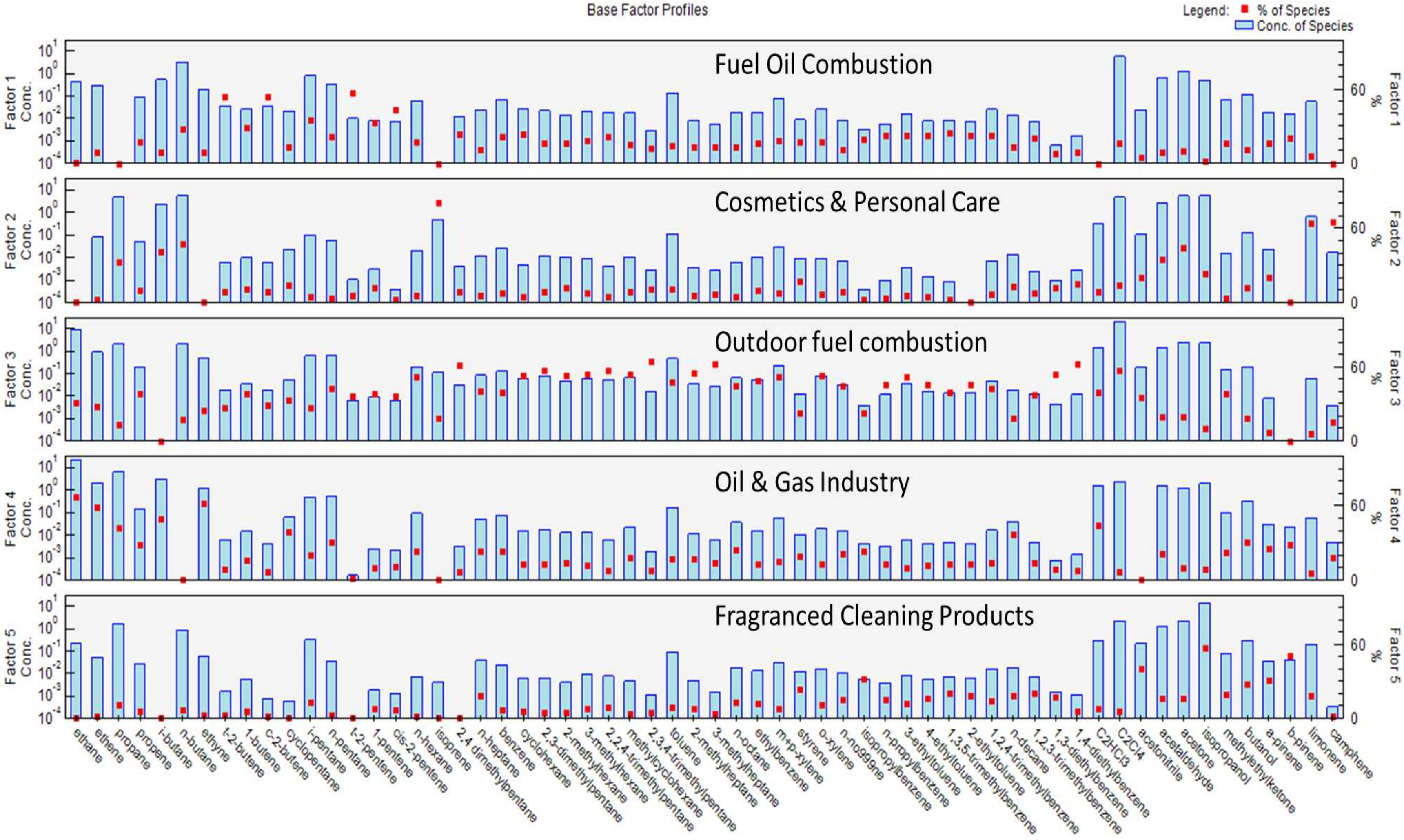

Figure 17: Non-kitchen Sampling Base Factor Profiles

Sensitivity analyses 5.3

Descriptive Statistics Sensitivity Analysis 5.3.1

A sensitivity analysis was conducted to evaluate whether different statistical approaches would influence the ranking of the most prevalent VOC species. The primary method used in this study was the geometric mean, a standard approach that reduces the influence of extreme values and ensures that only analytes detected and quantified in at least 25% of samples were included in the top ten list. Additionally, methane was removed from the dataset to focus on VOCs more relevant to indoor air quality concerns. To assess the robustness of this approach, the results derived from the geometric mean were compared to those obtained using the arithmetic mean (standard mean).

The following plots (Figures 18 & 19) display indoor and outdoor VOC concentrations in descending order, as ranked by the arithmetic mean. Notable differences were observed in both the ordering and composition of the top ten lists depending on the statistical method used. For indoor concentrations, when applying the geometric mean, isopropanol emerged as the highest concentration analyte, whereas ethane was ranked highest when using the arithmetic mean. Most species remained consistent across the two ranking methods, with some variations in order. However, the removal of methane from the dataset led to i-pentane replacing methane in the indoor rankings.

For outdoor concentrations, the species identified by the geometric mean remained the same as those determined by the arithmetic mean, with the exception of methane, which was replaced by ethyne. Although the ranking order changed, ethane remained the dominant VOC across both methods.

These differences highlight the sensitivity of ranking outcomes to the chosen statistical approach. The arithmetic mean is more influenced by extreme values, whereas the geometric mean provides a more stable representation of central tendencies in the dataset. Given that the geometric mean minimizes distortion from outliers, its use in this study was confirmed as the most appropriate method for descriptive statistics of VOC concentrations.

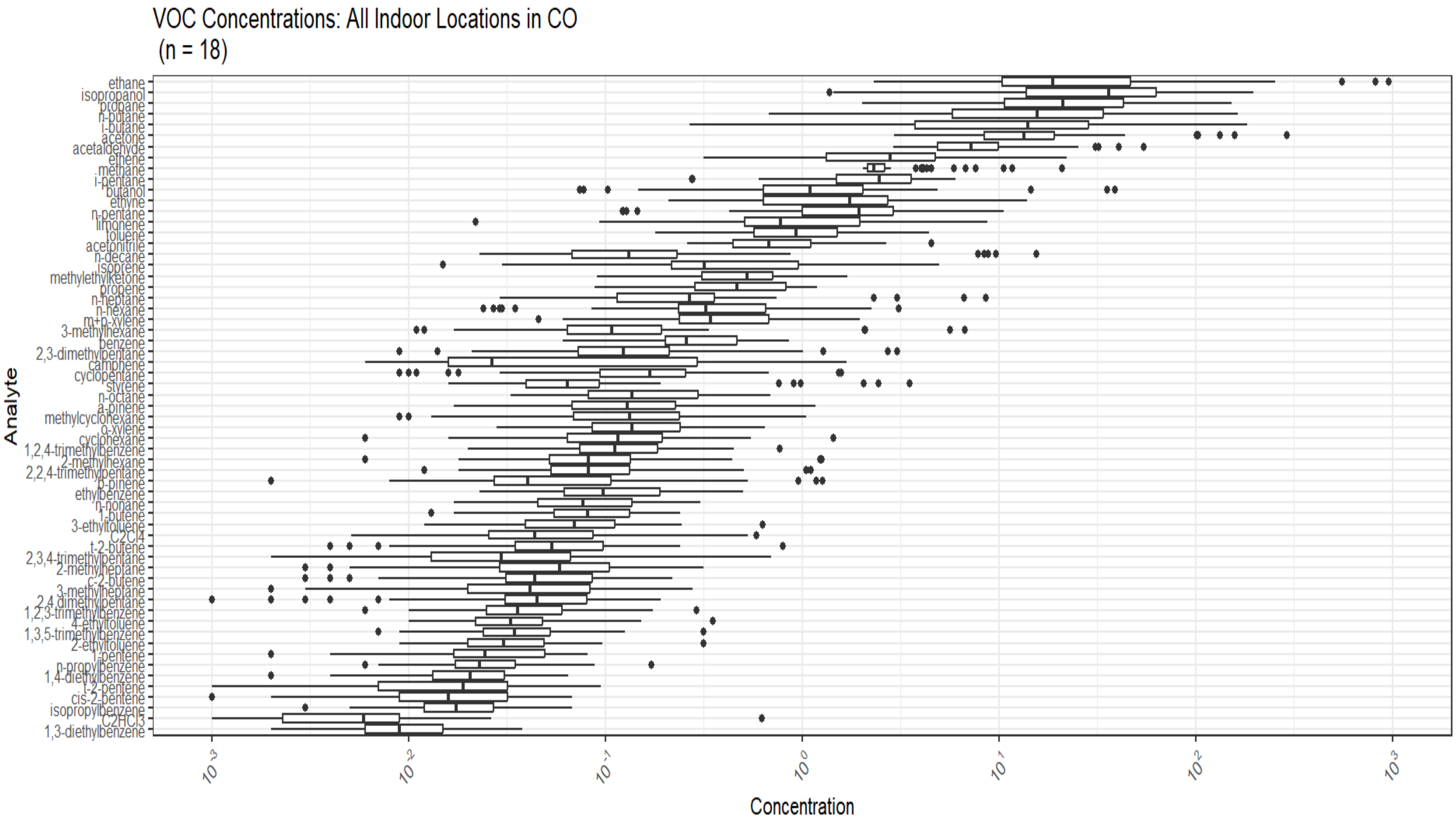

Figure 18: Indoor VOC Concentrations using Standard Mean

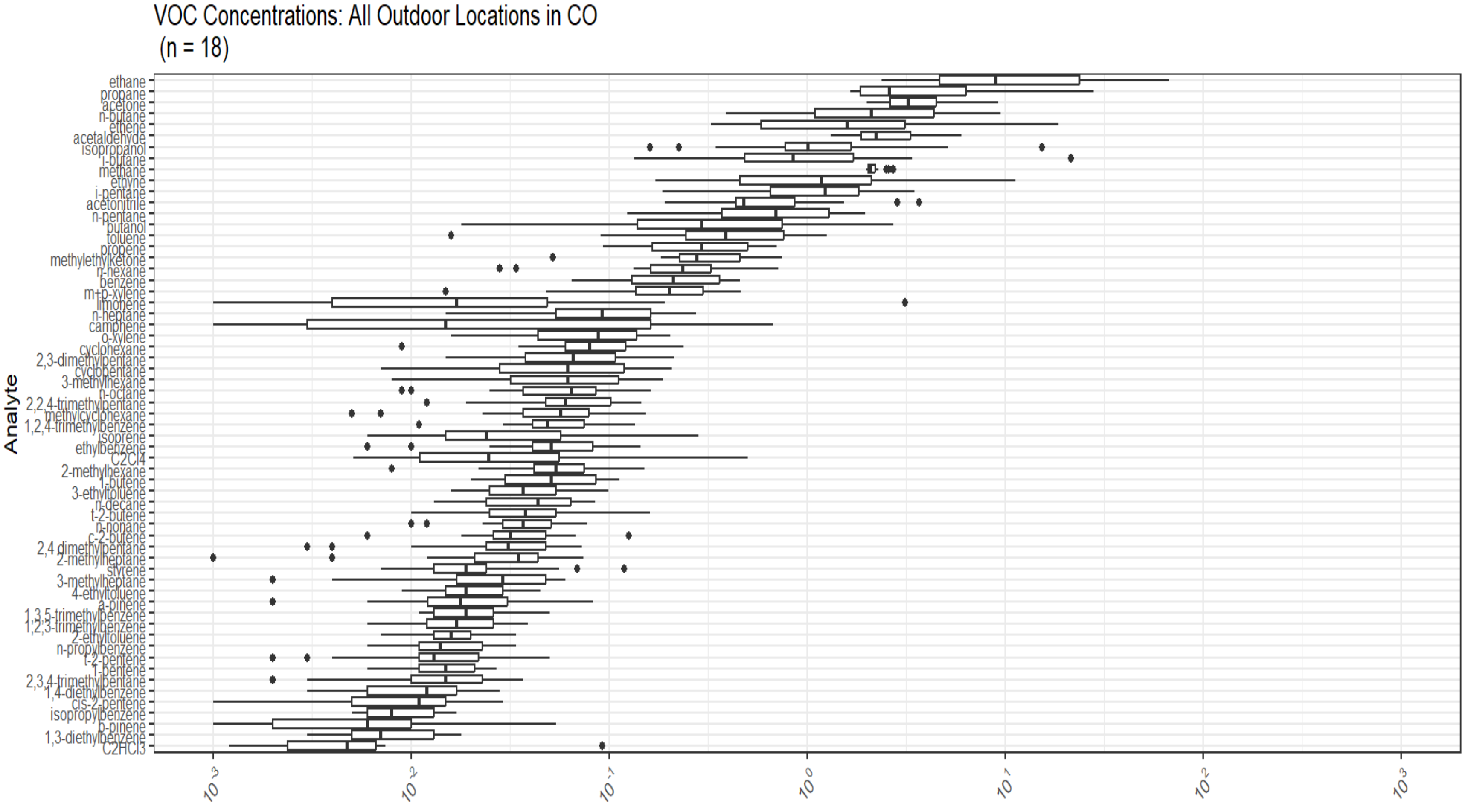

Figure 19: Outdoor VOC Concentrations using Standard Mean

PMF Sensitivity Analysis 5.3.2

The primary sensitivity analysis utilized for PMF factor solution selection was conducted using mapping of bootstrap factors to the base factors. In the following tables, boot factor mapping and results have been quantified. Factor solutions will be shown in descending order, for example from seven to three. The factor that contains the highest values shown in the yellow highlighted cells across the descending diagonal, is the factor most representative of the sample set. Values closest to 100 are considered to be the most ideal, as well as having low unmapped values in the far right column of each table. Values in the yellow highlighted cells below 70, particularly if there are multiple low values detected, lead to that factor solution being discarded as being a sub optimal representation of the data set.

For example, following tables included factors ranging from three to seven. Where the three, four, six and seven factor solutions contained boot factor values ranging from 30 to 40 in some of the yellow highlighted cells. While the five-factor solution contained only values above 70. Leading to the five factor solution being identified as the most representative factor solution for the data.

The following tables (Table 2) show the mapping of bootstrap factors for cool season samples. The 3, 4 and 7 factor solutions were discarded given some low values and higher values of unmapped species. The 5 and 6 factor solutions were both considered, though the 6-factor solution did not provide additional insight compared to the 5-factor solution. The 5-factor solution was determined to be most optimal.

Table 2: Cool Season Sampling Bootstrapping Factor Mapping

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Unmapped
Boot Factor 1	86	1	4	6	0	0	1	2
Boot Factor 2	1	71	15	2	0	9	0	2
Boot Factor 3	0	1	92	3	0	3	0	1
Boot Factor 4	1	0	1	94	0	0	0	4
Boot Factor 5	1	4	13	5	65	3	1	8
Boot Factor 6	2	2	7	2	0	85	1	1
Boot Factor 7	1	0	15	3	0	3	75	3

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Unmapped
Boot Factor 1	83	4	2	1	5	4	1
Boot Factor 2	6	88	0	0	4	0	2
Boot Factor 3	5	3	89	0	1	2	0
Boot Factor 4	5	4	1	74	7	5	4
Boot Factor 5	2	2	1	0	88	1	6
Boot Factor 6	0	1	2	1	4	92	0

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Unmapped
Boot Factor 1	96	0	0	2	0	2
Boot Factor 2	8	80	0	6	1	5
Boot Factor 3	11	8	65	7	1	8
Boot Factor 4	2	1	0	93	2	2
Boot Factor 5	12	7	1	3	71	6

	Factor 1	Factor 2	Factor 3	Factor 4	Unmapped
Boot Factor 1	99	0	0	1	0
Boot Factor 2	11	72	0	10	7
Boot Factor 3	14	0	72	6	8
Boot Factor 4	4	1	0	91	4

	Factor 1	Factor 2	Factor 3	Unmapped
Boot Factor 1	72	3	11	14
Boot Factor 2	5	77	9	9
Boot Factor 3	1	0	99	0

The following tables (Table 3) include the sensitivity analysis for warm season samples. Here 4 to 7 factor solutions were ran to test for best fit. The 4, 6 and 7 factor solutions were discarded due to the inclusion of low values highlighted in yellow, and high unmapped values. Specifically noting a value of 34 in the four-factor solution for Boot Factor 1, a value of 41 in the 6-factor solution for Boot Factor 1, and a value of 47 in the 7-factor solution for Boot Factor 6. Suggesting that the 5-factor solution is the most representative of the data set.

Table 3: Warm Season Sampling Bootstrapping Factor Mapping

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Unmapped
Boot Factor 1	81	0	2	4	1	0	3	9
Boot Factor 2	1	79	3	3	2	0	1	11
Boot Factor 3	0	0	87	3	3	0	3	4
Boot Factor 4	1	0	1	90	3	0	2	3
Boot Factor 5	0	1	3	0	84	0	5	7
Boot Factor 6	1	4	5	8	5	47	9	21
Boot Factor 7	0	0	0	0	0	0	96	4

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Unmapped
Boot Factor 1	41	5	9	2	7	9	27
Boot Factor 2	0	79	2	2	5	2	10
Boot Factor 3	0	0	92	1	3	1	3
Boot Factor 4	0	2	2	84	4	3	5
Boot Factor 5	0	0	0	2	92	0	6
Boot Factor 6	0	0	0	2	2	94	2

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Unmapped
Boot Factor 1	87	0	1	3	4	5
Boot Factor 2	5	69	2	1	2	21
Boot Factor 3	5	0	85	0	2	8
Boot Factor 4	2	2	3	72	3	18
Boot Factor 5	1	0	0	0	94	5

	Factor 1	Factor 2	Factor 3	Factor 4	Unmapped
Boot Factor 1	34	21	22	2	21
Boot Factor 2	0	96	1	2	1
Boot Factor 3	1	0	94	0	5
Boot Factor 4	0	3	8	82	7

Next, the sensitivity analysis for kitchen samples is shown in the tables as follows (Table 4). Similarly, to seasonality sensitivity analysis, the 5-factor solution was determined to be the most representative of the kitchen-based samples. Factors 3, 4 and 6 were discarded due to lower boot factor numbers, while the 5 and 7 factor solution were considered in greater depth. Both factor solutions had comparable rates of unmapped factors, 58 and 56 respectively. The 5-factor solution was selected given that the 7-factor solution did not provide cleaner separation or further explanation than the 5-factor solution.

Table 4: Kitchen Sampling Bootstrapping Factor Mapping

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Unmapped
Boot Factor 1	80	0	0	1	9	4	1	5
Boot Factor 2	0	70	4	3	4	0	2	17
Boot Factor 3	0	0	97	0	0	0	0	3
Boot Factor 4	1	1	0	94	0	0	4	0
Boot Factor 5	0	0	0	0	78	0	0	22
Boot Factor 6	1	14	4	4	3	68	0	6
Boot Factor 7	1	1	1	0	0	0	94	3

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Unmapped
Boot Factor 1	79	3	0	8	1	4	5
Boot Factor 2	0	98	0	0	0	0	2
Boot Factor 3	0	0	76	0	0	0	24
Boot Factor 4	0	0	0	84	0	0	16
Boot Factor 5	0	0	0	16	75	2	7
Boot Factor 6	2	2	3	14	3	62	14

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Unmapped
Boot Factor 1	88	0	0	0	0	12
Boot Factor 2	1	86	0	0	1	12
Boot Factor 3	0	6	85	0	1	8
Boot Factor 4	0	0	0	68	6	26
Boot Factor 5	0	0	0	0	100	0

	Factor 1	Factor 2	Factor 3	Factor 4	Unmapped
Boot Factor 1	98	0	0	0	2
Boot Factor 2	1	74	0	0	25
Boot Factor 3	3	2	73	2	20
Boot Factor 4	5	2	0	86	7

	Factor 1	Factor 2	Factor 3	Unmapped
Boot Factor 1	89	2	2	7
Boot Factor 2	1	90	0	9
Boot Factor 3	16	0	64	20

Finally, sensitivity analysis was conducted for non-kitchen room sampling. Shown in the tables below (Table 5), is the bootstrap factor mapping analysis for this subset of samples. The non-kitchen room bootstrapping analysis was simple given Boot Factor values in the 30s and 40s for all factor solutions aside from the 5-factor solution. Factors 4, 6 and 7 also contained higher values in the unmapped criterium. Subsequently, the 5-factor solution was determined to be the most representative solution for the non-kitchen room samples.

Table 5: Non-Kitchen Sampling Bootstrapping Factor Mapping

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Unmapped
Boot Factor 1	81	0	2	4	1	0	3	9
Boot Factor 2	1	79	3	3	2	0	1	11
Boot Factor 3	0	0	87	3	3	0	3	4
Boot Factor 4	1	0	1	90	3	0	2	3
Boot Factor 5	0	1	3	0	84	0	5	7
Boot Factor 6	1	4	5	8	5	47	9	21
Boot Factor 7	0	0	0	0	0	0	96	4

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Unmapped
Boot Factor 1	41	5	9	2	7	9	27
Boot Factor 2	0	79	2	2	5	2	10
Boot Factor 3	0	0	92	1	3	1	3
Boot Factor 4	0	2	2	84	4	3	5
Boot Factor 5	0	0	0	2	92	0	6
Boot Factor 6	0	0	0	2	2	94	2

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Unmapped
Boot Factor 1	87	0	1	3	4	5
Boot Factor 2	5	69	2	1	2	21
Boot Factor 3	5	0	85	0	2	8
Boot Factor 4	2	2	3	72	3	18
Boot Factor 5	1	0	0	0	94	5

	Factor 1	Factor 2	Factor 3	Factor 4	Unmapped
Boot Factor 1	34	21	22	2	21
Boot Factor 2	0	96	1	2	1
Boot Factor 3	1	0	94	0	5
Boot Factor 4	0	3	8	82	7

6. DISCUSSION

Indoor air quality (IAQ) is increasingly recognized as a critical factor in human health, with volatile organic compounds (VOCs) being among the primary pollutants of concern. VOCs are emitted from a variety of indoor sources, including building materials, personal care products, cleaning agents, and combustion processes, and exposure has been linked to a range of adverse health effects, from mild irritation to chronic respiratory diseases and carcinogenic risks. Prior research has demonstrated that indoor VOC concentrations often exceed outdoor levels, posing increased risks due to the significant amount of time people spend indoors—particularly in workplaces. However, the relative contributions of indoor versus outdoor sources and the seasonal variability of VOC concentrations have not been extensively examined, especially in occupational settings over long-term sampling periods.

The results of this study confirm that indoor VOC concentrations were significantly higher than outdoor concentrations, consistent with previous literature. The findings were reinforced by indoor-to-outdoor (I/O) ratios, which demonstrated that across the 61 VOCs sampled, only acetonitrile had a higher outdoor concentration that contributed meaningfully to indoor environments. For all remaining 60 VOCs, I/O ratios above 1.0 indicated that indoor sources were the dominant contributors. Among the VOCs with the highest I/O ratios—ranging from six to nearly 20 times greater indoors than outdoors—the primary contributors were linked to personal care and cleaning products. These included acetone, styrene, limonene, α-pinene, n-butane, i-butane, isoprene, β-pinene, isopropanol, and n-decane. Factor analysis using Positive Matrix Factorization (PMF) further supported these findings, with the dominant contributors in both kitchen and non-kitchen rooms being associated with fragranced household cleaning products and cosmetics.

The relative dominance of VOC sources differed notably between kitchen and non-kitchen spaces. PMF analysis of kitchen-only rooms indicated that Factors 1 and 3 were attributed to indoor and outdoor fuel combustion, while Factors 2 and 5 were associated with building materials, flooring, and fragranced cleaning products. In contrast, non-kitchen rooms showed Factor 5 as the dominant contributor, strongly linked to cleaning products, while Factors 1, 3, and 4 were attributed to fuel combustion and emissions from the oil and gas industry. The reversal of leading source factors between kitchen and non-kitchen rooms suggests that kitchens experience higher exposure to fuel combustion emissions, whereas non-kitchen rooms are more affected by cleaning and personal care product use. Notably, benzene, a well-established carcinogenic air pollutant, was primarily attributed to kitchen-based fuel combustion sources, reinforcing the need for enhanced ventilation in cooking environments.

VOC concentrations and dominant source factors also varied by season. Warm-season PMF analysis showed that Factors 1, 2, 4, and 5 were primarily associated with oil and gas industry emissions, combustion processes, and industrial sources, while Factor 3 was linked to household building materials. Conversely, in the cool season, Factors 2 and 4 were strongly attributed to cosmetics, personal care products, air fresheners, and cleaning products, whereas Factors 1, 3, and 5 were linked to industrial emissions, fuel combustion, and oil and gas sources. These findings suggest that oil and gas emissions and combustion processes play a more dominant role in indoor air pollution during warmer months, while personal care and household product emissions become more prominent in the cool season. A potential explanation is that reduced ventilation during colder months allows cleaning product emissions to accumulate indoors, whereas warmer months see increased outdoor contributions due to higher infiltration rates. These seasonal differences suggest that increasing ventilation while using cleaning products during cooler months may improve IAQ outcomes.

The findings of this study contribute to the broader field of exposure science and IAQ research by reinforcing the importance of understanding source contributions to indoor VOC levels. The strong influence of cleaning and personal care products on indoor air pollution, particularly in non-kitchen rooms, underscores the need for regulatory policies that limit the use of high-emission VOC products or promote low-emission alternatives. In workplace settings, these findings highlight the importance of implementing better IAQ monitoring and ventilation strategies to mitigate exposure risks. Additionally, individuals can take steps to improve their indoor air quality by making informed product choices and increasing ventilation, particularly when using fragranced cleaning products or personal care items.

While this study provides valuable insights into VOC contributions and seasonal trends, several areas warrant further investigation. Notably, IAQ research has traditionally been outdoor air-centric, with indoor air monitoring protocols lagging behind despite growing evidence that indoor air quality often exceeds outdoor pollution levels in terms of harmful exposures. Future studies should explore:

1. The impact of indoor VOC emissions on outdoor air quality, particularly in urban environments where high indoor emissions may contribute to outdoor pollution.
2. Key factors driving seasonal shifts in VOC concentrations, including meteorological conditions and behavioral differences in indoor activities.
3. Optimizing seasonal intervention strategies, such as improving ventilation during peak emission periods or promoting season-specific IAQ policies.

4. Assessing ventilation system effectiveness across seasonal variations, to determine how air handling systems influence indoor pollutant dynamics throughout the year.
5. Analyzing impacts of wildfires occurring concurrently with IAQ sampling, assessing differences in I/O ratios during times with and without wildfires occurring.

A key strength of this study is its comprehensive design, which aimed to support underserved communities by assessing and recommending improvements for their indoor air quality. The inclusion of a diverse set of workplace environments—ranging from healthcare facilities to community centers and detention centers—provides a broad perspective on IAQ challenges across different settings. Additionally, the study leveraged an extensive range of air quality measurements, allowing for a multi-faceted understanding of IAQ across different environments.

However, several limitations should be acknowledged. First, VOC sampling was conducted in 18 of the 50 total study sites, primarily due to budget and labor constraints. VOC sampling using SUMMA canisters required an additional site visit, increasing logistical and laboratory costs, which constrained the number of locations where it was feasible. Additionally, the disparity in sample sizes between kitchen and non-kitchen spaces (9 versus 75 samples) may have limited the ability to fully resolve cooking-related source contributions.

Another limitation was the challenges associated with PMF source separation. The EPA PMF tool is primarily designed for particulate matter ($PM_{2.5}$) analysis, which may have impacted its ability to fully resolve VOC-specific source profiles. Furthermore, the use of outdoor sampling methodologies for indoor environments presents challenges, as certain indoor VOC sources may not be well-captured using traditional outdoor air quality monitoring protocols.

7. CONCLUSION

In conclusion, this study adds value to the field of indoor air quality research by characterizing the sources of VOCs in diverse workplace environments across Colorado. The findings highlight the importance of considering both indoor sources (particularly cleaning products and personal care items) and outdoor infiltration in managing IAQ. Seasonal variations also play a critical role in determining VOC concentrations, suggesting that interventions should be tailored to specific times of the year. The results of this study provide important implications for policy, workplace management, and consumer behavior, as well as avenues for future research aimed at improving indoor air quality and reducing exposure to harmful pollutants.

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9. APPENDICES

9.1 Indoor/Outdoor Mixing Ratios

	Analyte	**Indoor (ppb)**	**Outdoor (ppb)**	**I/O**
1	acetonitrile	0.87425714	0.903411765	0.967728
2	ethyne	2.44851429	1.836352941	1.333357
3	1,3-diethylbenzene	0.01154286	0.008647059	1.334888
4	t-2-pentene	0.02284286	0.016588235	1.377052
5	C2Cl4	0.08271429	0.059805294	1.38306
6	benzene	0.33144286	0.230705882	1.436647
7	methane	3.2079	2.181941176	1.470205
8	ethene	4.4242	2.927058824	1.511483
9	2,4 dimethylpentane	0.05714286	0.035823529	1.595121
10	propene	0.54212857	0.338235294	1.602815
11	c-2-butene	0.06388571	0.038882353	1.643052
12	n-hexane	0.50112857	0.297705882	1.683301
13	methylethylketone	0.57092857	0.331764706	1.720884
14	1-butene	0.09722857	0.056411765	1.723551
15	n-propylbenzene	0.02984286	0.016941176	1.761558
16	C2HCl3	0.01470343	0.008321765	1.766864
17	1,4-diethylbenzene	0.02332857	0.012941176	1.802662
18	cyclohexane	0.15984286	0.088647059	1.803138
19	t-2-butene	0.08148571	0.043882353	1.856913
20	2,2,4-trimethylpentane	0.12941429	0.069294118	1.867609
21	cis-2-pentene	0.02174286	0.011588235	1.876287
22	o-xylene	0.16804286	0.088764706	1.893127
23	4-ethyltoluene	0.04391429	0.023058824	1.904446
24	1-pentene	0.0307	0.016117647	1.904745
25	3-ethyltoluene	0.08408571	0.044	1.911039
26	i-pentane	2.69787143	1.388352941	1.943217
27	1,3,5-trimethylbenzene	0.04335714	0.021941176	1.976063
28	3-methylheptane	0.05735714	0.028705882	1.998097
29	m+p-xylene	0.45745714	0.227647059	2.009502
30	ethylbenzene	0.12587143	0.061529412	2.045712
31	2-methylheptane	0.07467143	0.035352941	2.11217
32	2-ethyltoluene	0.03977143	0.018470588	2.15323
33	1,2,4-trimethylbenzene	0.13905714	0.063529412	2.188862
34	2-methylhexane	0.13402857	0.059470588	2.253695
35	toluene	1.10857143	0.487352941	2.274679
36	camphene	0.22965714	0.100529412	2.284477

37	isopropylbenzene	0.02105714	0.009176471	2.294689
38	n-nonane	0.09808571	0.042176471	2.325603
39	1,2,3-trimethylbenzene	0.04704286	0.019529412	2.408821
40	n-pentane	2.31094286	0.834705882	2.768571
41	n-octane	0.20198571	0.071411765	2.828466
42	methylcyclohexane	0.19178571	0.067529412	2.840032
43	2,3-dimethylpentane	0.24344286	0.085352941	2.852191
44	cyclopentane	0.22887143	0.080235294	2.852503
45	acetaldehyde	10.07488571	2.893705882	3.481655
46	butanol	2.60464286	0.640294118	4.067885
47	ethane	75.21272059	18.19023529	4.134786
48	3-methylhexane	0.35484286	0.076764706	4.622474
49	2,3,4-trimethylpentane	0.07478571	0.016058824	4.656986
50	n-heptane	0.54	0.113588235	4.754014
51	propane	34.04858571	5.750882353	5.920585
52	acetone	25.15697143	3.972764706	6.332359
53	styrene	0.21401429	0.028823529	7.424985
54	limonene	1.74201429	0.217705882	8.001687
55	a-pinene	0.19522857	0.022647059	8.620482
56	n-butane	28.85227143	3.071705882	9.392915
57	i-butane	26.89671429	2.361294118	11.39067
58	isoprene	0.85511429	0.063470588	13.47261
59	b-pinene	0.12655714	0.009176471	13.79148
60	isopropanol	44.44515714	2.386588235	18.62288
61	n-decane	0.86917143	0.043941176	19.78034