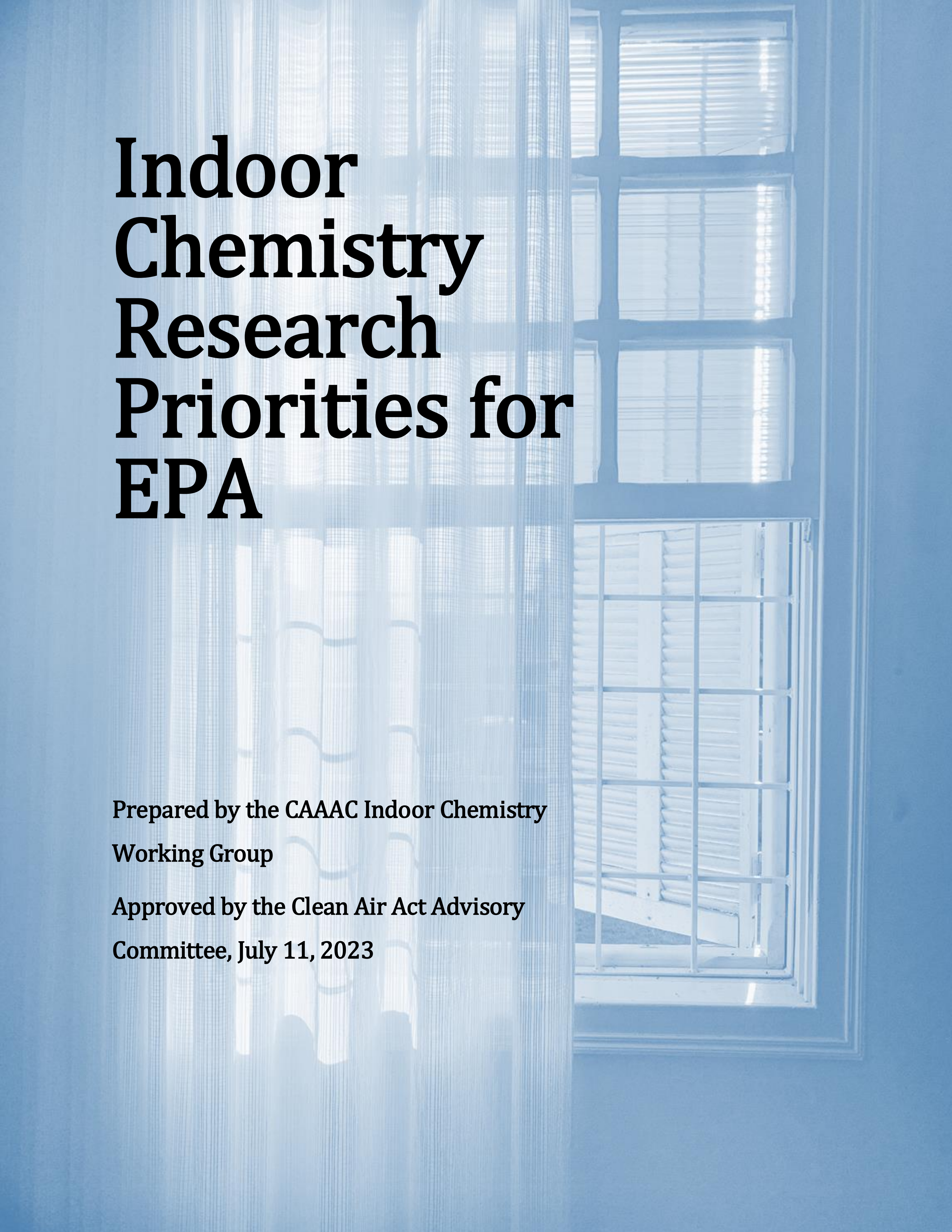

Indoor Chemistry Research Priorities for EPA

Prepared by the CAAAC Indoor Chemistry Working Group

Approved by the Clean Air Act Advisory Committee, July 11, 2023

Table of Contents

Indoor Chemistry Working Group Members:

- William Bahnfleth, Ph.D., P.E. (Chair)
- Dan Greenbaum
- Gary Jones
- Max Sherman, Ph.D.

1 Introduction

The National Academies of Science, Engineering and Medicine (NASEM) recently issued a consensus report entitled "Why Indoor Chemistry Matters" (2022) that reviews the current state of the discipline of indoor chemistry. Sponsors of the report included the Centers for Disease Control and Prevention, the National Institute of Environmental Health Sciences, the Environmental Protection Agency (EPA), and the Alfred P. Sloan Foundation.

This Clean Air Act Advisory Committee (CAAAC) prepared this report at the request of the EPA Indoor Environments Division Office of Radiation and Indoor Air, which asked that it:

> Provide recommendations on prioritizing the research needs identified by the NASEM in their consensus report: Why Indoor Chemistry Matters. Focus on priorities for short term research (1-3 years) that could inform public health guidance and building practices for improving Indoor Air Quality (IAQ) in homes, schools, and commercial and office buildings.

The Statement of Task given to the authoring NASEM Committee on Emerging Science on Indoor Chemistry was as follows:

> The National Academies of Sciences, Engineering, and Medicine will convene an ad hoc committee of scientific experts and leaders to consider the state-of-the-science regarding chemicals in indoor air. Specifically, the committee will focus on: (1) new findings about previously under-reported chemical species, chemical reactions, and sources of chemicals, as well as the distribution of chemicals; and (2) how indoor chemistry findings fit into context of what is already known about the link between chemical exposure, air quality, and human health.
>
> The committee's consideration of this information will lead to a report with findings and recommendations regarding: (1) key implications of the scientific research, including potential near-term opportunities for incorporating what is known into practice; and (2) where additional chemistry research will be most critical for understanding the chemical composition of indoor air and adverse exposures. As appropriate, opportunities for advancing such research by addressing methodological or technological barriers or enhancing coordination or collaboration will be noted. The committee will also provide recommendations for communicating its findings to affected stakeholders. The indoor environments focused on in this study will be limited to non-industrial exposure within buildings.

In response to this charge, the NASEM consensus committee prepared a report comprising seven chapters:

1. Introduction
2. Primary Sources and Reservoirs of Chemicals Indoors
3. Partitioning of Chemicals in Indoor Environments
4. Chemical Transformations
5. Management of Chemicals in Indoor Environments
6. Indoor Chemistry and Exposure
7. A Path Forward for Indoor Chemistry

The NASEM report is wide ranging and addresses issues related to academia and public agencies well beyond EPA's primary focus. It offers an equally wide-ranging set of recommendations, some of which relate to research and some of which do not. The recommendations of the report related to research are presented chapter by chapter and are not prioritized or categorized with respect to timing (*i.e.*, whether they are or should be near-term or longer-term priorities.)

A small working group of CAAAC members was appointed to carry out the EPA charge. Its recommendations are presented in this report, which has been reviewed and approved by the full CAAAC.

The request to CAAAC differs from the statement of task to the NASEM committee. As noted, the NASEM report recommendations are neither prioritized nor specific to a desired timeframe. In addition, the NASEM committee was not asked to provide a complete short-term research agenda. Consequently, the CAAAC working group's approach was to take the recommendations of the NASEM report as a starting point, which it augmented as necessary. Every conclusion and recommendation in the report – 43 in all – was reviewed for relevance to the charge from EPA. Based on this review, some were excluded either as not being feasible as part of a 1–3-year short term program or for lack of relevance to development of applicable public health guidance.

Recommendations meeting these screening criteria that pointed to specific research needs were assigned priority levels and grouped into higher level categories: Human Behavior, Health Disparities and Environmental Justice, and Air Cleaners. The working group felt that Contaminants of Concern (CoC) are an additional important category not addressed by recommendations of the NASEM report that should be included in its recommendations. The working group used these four categories to structure its recommendations. In some cases, verbatim recommendations from the

NASEM report were separated into multiple, more narrowly focused recommendations and reworded to be more responsive to the EPA charge. Some recommendations the working group believed had value, typically overarching in nature, are also included in this report.

2 Prioritization of NASEM Recommendations

This section provides the prioritization of recommendations from the NASEM report explicitly requested by EPA, categorized as overarching recommendations and recommendations in the three focus areas of the NASEM report identified by the working group: Human Behavior, Health Disparities and Environmental Justice, and Air Cleaners. Section 3 provides recommendations on research needs for Contaminants of Concern. When recommendations are quoted or paraphrased from the NASEM report, they are followed by a note indicating the referenced item in Appendix A of this report and the chapter of the NASEM report from which it was taken.

2.1 Overarching Recommendations

In reviewing the extensive recommendations of the NASEM Indoor Air Chemistry Committee, the CAAAC working group concluded that EPA and its federal partners should prioritize acquisition of actionable data and research to link sources with exposures and understand impacts of mixtures on health. Research is needed that provides greater resolution of spatial and temporal trends in chemical emissions indoors, and how these vary for both chronic and episodic sources. Specific needs include improved understanding of the combined influence of ventilation rates, humidity, and temperature on chemical emissions indoors, and interaction of the indoor and outdoor environment and its influence on indoor sources and exposures, especially for SVOCs. Better understanding of sources would provide more actionable information to control sources and, consequently, exposures. (Item 1, Chapter 2)

To accomplish this, the Working group identified several key components:

- Enhanced Exposure Assessment: EPA and partners should review current science of indoor chemistry to define gaps in current exposure assessment methods or data collection. Examples include identification of novel chemicals or chemical reaction products to include in field exposure studies (*e.g.*, ozonolysis intermediates), evaluation of influential behaviors (*e.g.*, window-opening), and collection of market data for products of interest (*e.g.*, oxidizing air cleaners or fragranced products). (Item 20, Chapter 6)
- Engagement of Key Health Effects Expertise: Researchers who study toxicology and epidemiology and their funders should prioritize resources toward understanding indoor

exposures to contaminants, including those of outdoor origin that undergo subsequent transformations indoors. (Item 32, Chapter 7)

- Dissemination for Decisions: Researchers should proactively engage in links that connect research to application throughout the indoor chemistry research process — for example, at the dissemination stage, by engaging with technical and standard-writing committees, presenting at conferences attended by practitioners, and disseminating the significance of research findings in social and mass media. (Item 39, Chapter 7)

2.2 Human Behavior

Exposure to and health effects resulting from indoor air chemistry are directly related to human behavior. Research to address such exposures and health effects will need to:

- Expand into the chemistry associated with human occupancy, behavior, and activities, especially identification of processes that alter exposure to chemicals. Common human activities, such as cooking, cleaning, smoking, and personal care product use lead to chemical change that needs to be fully investigated. The complete suite of transformation products that arise when these primary emissions react in the indoor environment is unknown. (Item 11, Chapter 4)
- Deepen understanding of human behavior and time-activity patterns as they relate to indoor chemistry. Addressing this critical knowledge gap would likely contribute to greater understanding of exposure variability. For example, factors such as clothes-laundering, handwashing, window- and door-opening, spending time indoors or outdoors, cooking, cleaning, and engaging in leisure activities can drive significant differences in chemical exposures. Detailed, representative behavioral data will be increasingly valuable for models of physical processes and exposure. In recent years, the scientific community has learned how the presence of a human body mediates indoor chemistry, including gas-phase composition, generation of VOCs, and surface reactivity. It is likely that the collection of behavioral data will accelerate in the coming years. Efforts to ensure the representativeness of such data are needed if they are to be used for model training, while protecting data privacy and sustaining the highest-caliber research ethics. (Item 24, Chapter 6)
- Improve models through better integration of an understanding of human behavior. Human time-activity patterns (*i.e.*, where people spend their time), habits and practices, and behavioral data associated with indoor chemistry warrant significantly more study that keeps demographic differences in mind. Opportunities also exist to support and nurture

modeling consortia or modeling hubs that are cross-disciplinary and include close collaboration with experimentalists. (Item 26, Chapter 6)

- Federal agencies should design and regularly implement an updated National Human Activity Patterns Survey. Federal and state agencies should add survey questions in existing surveys that capture people's activities in indoor environments as they relate to indoor chemistry and indoor chemical exposures. (Item 38, Recommendation 11, Chapter 7)

2.3 Health Disparities and Environmental Justice

There is growing awareness of the significant disparities in exposures and effects from air pollution experienced by environmental justice communities. These disparities occur both in outdoor and indoor environments. To begin to address these in the context of indoor air chemistry exposures, EPA and its partners should:

- Include environmental justice communities in the wide range of indoor environments they study and engage these communities in formulating research priorities and recommendations for future indoor air quality standards. (Item 40, Chapter 7)
- Develop more harmonized measures to characterize indoor exposure disparities. A sparse number of studies reproducibly demonstrate that demographic and socioeconomic factors can enhance susceptibility to chemical exposures, but the evidence base for this conclusion is incomplete and data poor. As patterns and predictors of indoor chemical exposures and exposure variability become better understood, it will be important to standardize and make widely available datasets that fully capture these differences. Future work that comprehensively characterizes indoor exposures across a more diverse array of settings would have significant value for a range of real-world applications, including individual-, community-, and policy-level decision making. Expanded exposure datasets could be used in concert with the National Health and Nutrition Examination Survey (NHANES) biomonitoring dataset. (Item 21, Chapter 6)
- Develop methodological and technological tools to make direct measurement of exposures easier, more convenient, and lower cost, especially to chemical mixtures, at scales that meaningfully improve the performance of exposure modeling and close gaps in understanding relationships between indoor environmental co-exposures to many chemicals and health outcomes, including persistent environmental health disparities. Tools to enhance exposure monitoring based on microenvironmental measurements should extend beyond measuring species concentrations to also track occupancy patterns in indoor

environments, as these patterns can influence emissions, ventilation, and pollutant removal. (Item 22, Chapter 6)

2.4 Air Cleaners

Given the recently heightened public interest in indoor air quality, device manufacturers, researchers, and public health professionals need to communicate clearly to consumers about the efficacy and chemical exposure consequences of different air-cleaning approaches. The lack of testing and regulation has led to rampant unsubstantiated claims about efficacy and health benefits of devices. The potential health risks and benefits resulting from their use warrant further investigation and potential certification or regulatory oversight. Based on the current state of knowledge, the NASEM committee cautions against approaches that induce secondary chemistry in occupied settings, unless the benefits demonstrably outweigh the risks of exposure to chemical reactants and byproducts. (Item 19, Chapter 5)

To accomplish this:

- Testing approaches need to be developed that consider both efficacy and byproduct formation in a representative range of real-world environments (*e.g.*, ultrafine particles, PM2.5, oxygenated VOCs including formaldehyde). Different chemicals induce different types of chemistry, so any testing approach must be flexible enough to account for likely products, and the complexity of indoor chemistry means that non-targeted analysis approaches could be useful. These tests and measurements can help inform a quantitative assessment of thresholds for health effects for relevant compounds. (Item 16, Chapter 5)
- Standardized consensus test methods could enable potential certification programs for air-cleaning products and services. Such test methods could help regulators determine whether action on these products and services is warranted. (Item 42, Chapter 7)
- And controlled field experiments are necessary to better understand the fundamental chemistry of emerging air-cleaning technologies, as well as mold and smoke remediation schemes. (Item 18, Chapter 5)

3 Prioritization for Contaminants of Concern

The NASEM report encourages prioritization for health impacts (Item 43, Chapter 7), but does not address the issue in any detail. Therefore, extant information was used to follow-up on that recommendation by identifying the high priority indoor air contaminants in the broad population—the so-called Contaminants of Concern (CoC). There are three broad categories of CoC in the indoor air: particles, biologicals, chemicals. It is appropriate to put the health impact of chemicals in context with that of the other CoCs, even though this discussion will focus on the chemical side.

- Particulate Matter (PM): Research has shown that particles are by far the most significant CoC. EPA has several active programs in that area that should be continued. A second order, but potentially significant effect, is the chemical make-up of these particles and the consequences of their deposition deep in the respiratory system where very fine particles may cross the air-blood interface. However, this report will not address this issue further as the near-term focus should be on PM reduction.
- Biologicals: Two classes of biologicals are important for indoor air: Infectious Aerosols (IA) such as those containing the viruses that cause COVID-19, influenza or measles, and non-infectious aerosols that may be toxins, allergens, or asthma triggers, such as mold or dust mite feces. While chemical reactions with disinfectants in the air could play a part in mitigating the health impacts of biologicals, this report will not address them further.
- Chemicals: Much of the NASEM report focuses on chemicals involved in indoor chemistry (*e.g.*, storage/partitioning or chemical reactions), but this does not include all chemicals found indoors. The most significant indoor chemical of that category is radon, which can be a significant hazard in certain regions. EPA has a robust, on-going program addressing radon; therefore, the topic will not be covered further in this report.

Indoor air researchers have quantified the health impacts of various CoCs. After excluding the CoCs noted above, two categories of chemicals stand out as having an outsized health impact: Reactive Oxygen Species (ROS) and Aldehydes. Issues related to them warrant near-term research effort which are summarized in the remainder of this section.

3.1 Reactive Oxygen Species (ROS)

While there is no consensus definition for ROS, it is generally agreed that they are a class of small chemicals containing a highly active oxygen atom capable of reacting with other molecules, particularly those in living cells. Primary ROS are typically neutral radical species (*e.g.*, ozone or hydroxyl radicals), but some are ions (*e.g.*, super-oxide or hydroxide ions), and some are neither ions nor radicals (*e.g.*, hydrogen peroxide) but are reactive, nonetheless. Several nitrogen and sulfur containing compounds with analogous structures (*i.e.*, so-called NOx and SOx) are included in ROS.

Many ROS are known, and others are believed, to have significant direct impacts on the human body, but quantitative studies are lacking on most ROS. The NASEM report includes extensive discussions of how ROS can react with other chemicals (*e.g.*, VOCs) to form various oxygenated species directly or through cascade reactions. These secondary compounds may have similarly significant health impacts, but the severity of these impacts at relevant exposure levels have not been quantified. Nevertheless, many technologies currently in the marketplace purport to safely use ROS for purposes as diverse as reducing airborne particulate levels, breaking down harmful chemical species, and inactivating pathogens.

In the National Ambient Air Quality Standards (NAAQS), the EPA has recognized the importance of three ROS: sulfur dioxide, nitrogen dioxide and ozone. Over its 50 years, the Clean Air Act (CAA) has been successful at significantly reducing the outdoor concentrations of these three compounds—albeit some more successfully than others.

Two of these compounds, ozone and nitrogen dioxide, have both indoor and outdoor sources. Both are in the top ten of list of harmful indoor air contaminants. It is not clear whether the critical chemistry happens in the air, on building surfaces, on a body surface (*e.g.*, lung tissue) or after being absorbed. Some basic research would be required to answer that question, but whatever the answer, adverse health impacts can be reduced by measures that reduce the indoor concentration.

Nitrogen dioxide (NO_2) is a by-product of combustion coming from both indoor and outdoor sources. In the last 50 years, emissions control research has reduced its emission quite substantially. Low NOx burners are available in consumer appliances like furnaces and water heaters. On the other hand, recent research has indicated that the health effects of nitrogen dioxide are worse than previously thought and stringency increases are underway.

Outdoor sources of NO_2 have been reduced substantially and under the current NAAQS there are no current non-attainment areas for nitrogen dioxide and only the Los Angeles basin is considered a maintenance area. There are, however, significant indoor sources, which elevates the importance of this ROS. The primary indoor sources are from unvented combustion including cooking, unvented heaters, smoking, as well as decorative appliances and consumer combustion products.

Nitrogen dioxide can be cleaned from the air: the two most common technologies are air washing and molecular filtration. Air washing involves dissolving the water-soluble gas and then removing it from the water; molecular filtration uses an adsorption medium to capture the gas, which can be regenerated as needed. Both these technologies are effective and are used in niche situations but are too costly or otherwise impractical for most buildings.

Since indoor sources of NO_2 are likely to pose the greatest risk, dilution could be an effective control strategy. However, the high deposition rate of NO_2 on surfaces is an additional removal mechanism that reduces the expected incremental effect of dilution. Regardless of the control technology, using it when not needed should be avoided. Unfortunately, there are not affordable sensors to aid in that determination.

Ozone (O_3) is a relatively long-lived ROS that can react to form other ROS and thus is an indicator contaminant for ROS. It can be generated both indoors and outdoors, but the processes for each are quite different.

Outdoors, ozone forms through photochemical processes, typically in urban basins. Non-attainment is much more severe for ozone than for the other two ROS under discussion. More than 1/3 of the US population lives in non-attainment areas. Ambient ozone concentrations tend to be diurnal and seasonal. Consequently, where mechanical ventilation is used, outdoor air may be a significant source of indoor ozone, as well as other ambient contaminants. For this reason, ASHRAE Standard 62.1 requires treatment for ozone of outdoor air in non-attainment areas. Overall, the indoor risk of outdoor ozone intrusion varies widely with building construction and HVAC system type.

The source of indoor-generated ozone is usually equipment that uses strong electric fields. In the past, some appliances intentionally generated ozone before the health hazards of exposure became known and widely disseminated by EPA. Some ozone generators are still used indoors for decontamination of spaces. Some products, including some air cleaners or ion generators that involve corona discharge, incidentally generate ozone. Underwriter's Laboratory has a standard (UL 2998) that can certify sufficiently low ozone generation. Electric equipment (*e.g.*, motors or even UL 2998 certified products) can emit ozone when operating improperly.

Because ozone is so reactive, there are more removal technologies available for it than for nitrogen dioxide. The two major technologies are adsorption (*e.g.*, activated carbon) and catalytic decomposition (including photocatalytic devices). These technologies are used in some larger buildings in non-attainment areas. Simple dilution is not an effective strategy when the primary source is outdoors.

Several research and guideline activities need to be undertaken to reduce the health impacts of ROS and related compounds:

- Evaluation of the need for improved venting of indoor combustion to reduce nitrogen dioxide levels indoors.
- Development of affordable sensors, for nitrogen dioxide and other indoor pollutants, that can be used to control ventilation or air cleaning systems.
- Examination of chemical transformations between the more common ROS (*e.g.*, ozone and nitrogen dioxide) and the most common airborne chemicals (*e.g.*, water) to form harmful secondaries (*e.g.*, HONO).
- Development of concentration limits for ROS in the indoor environment considering both their direct and indirect effects (*i.e.*, from indoor chemistry with other compounds)

3.2 Aldehydes

The class of chemicals known as aldehydes is known to be the most harmful to the indoor population of any class of VOC. The aldehydes found to be significant hazards indoors include formaldehyde (HCHO), acrolein, acetaldehyde and crotonaldehyde. While some of these chemicals are found outdoors, their sources are principally indoors, so they have not been regulated under the CAA.

Formaldehyde is far more important than the others, but acrolein can be important when there is incomplete combustion of large amounts of high-carbon fuels. This includes wood fires, large-scale candle burning, smoking, or cooking, especially indoor barbequing. Acrolein is a highly irritating gas at quite low concentrations.

Formaldehyde can be generated by those combustion activities as well. It can also be generated from other VOCs when interacting with ROS. However, the amount of generation of HCHO from these sources is small compared to the amount of formaldehyde emitted from indoor materials.

Formaldehyde is a gas at room temperature, but just barely, which is why it can become bound as a liquid in some materials or liquid mixtures. The formaldehyde in materials is mostly stored in the bulk media and has complex interactions with air and other materials. The NASEM report discusses partitioning of VOCs and that very much applies to formaldehyde.

The net result is that the concentration of formaldehyde is effectively buffered by the storage available in all materials. The implications of that are that any removal of formaldehyde from the air has less of an impact on the indoor concentration than if one assumed a constant emission rate. In the extreme that would mean the concentration of formaldehyde stays at some equilibrium level until the stock in the material was exhausted.

Formaldehyde can be cleaned out of the air by air washing, and the other methods discussed for ROS, but efficacy of such measures at lowering concentration will be greatly reduced by this buffering effect. Thus, much larger cleaners will be necessary to make substantial reductions.

The same inefficacy would be true for simple dilution, but that could be a more cost-effective approach. Regardless of whether the approach is air cleaning or enhanced dilution, it should only be done when necessary. Unfortunately, affordable sensors for formaldehyde are not available. Should the emission rate of HCHO be substantially reduced (*e.g.*, from low-emitting material requirements), explicit formaldehyde controls would not be necessary.

There are a variety of research needs related to aldehydes, particularly formaldehyde:

- Development of affordable sensors for nitrogen dioxide and other indoor air pollutants, that can be used to control ventilation or air cleaning systems.
- Reducing emission rates of formaldehyde in materials allows increased stringency in emission standards.
- Exploratory surveys and related health effects studies to determine if any other aldehydes produce significant harm.

4 Discussion

The priorities identified in this report are based on consideration of whole-population harm. For any given contaminant in any given region, there are likely to be sensitive populations that will suffer harm at significantly higher rates than the population average. These situations require resources to evaluate and, if necessary, to mitigate exceptionally.

This report is based on current knowledge about chemicals in the indoor air. Thousands of chemicals have been identified in the indoor air but there is perhaps an order of magnitude fewer for which there is enough data to quantify the harm to the population. The NASEM report also highlights second order effects (*e.g.*, impact of mixtures) that lack sufficient research. One cannot evaluate the risk posed by unknown hazards. To do so requires knowing which people are exposed to a given pollutant and the extent of harm, before considering sources and methods. The NASEM report has highlighted the need to do such exploratory research.

The NASEM report highlights issues related to chemical transformations. As these are secondary effects, only the ones likely to be important should be prioritized. These include the interactions of highly reactive chemicals such as ROS with commonly occurring constituents in the indoor environment such as nitrous acid (HONO). Such synergistic effects could be a contributing factor to the harm attributed to some ROS.

5 Summary

The NASEM report "Why Indoor Chemistry Matters" provides a broad, un-prioritized set of recommendations for future research ranging from fundamental chemistry to investigation of the health effects of indoor exposures. EPA's Indoor Environments Division charged CAAAC with extracting and prioritizing recommendations from the NASEM report "priorities for short-term research (1-3 years) that could inform public health guidance and building practices for improving Indoor Air Quality (IAQ) in homes, schools, and commercial and office buildings." This report presents that set of prioritized recommendations, which CAAAC working group has organized into four categories: Overarching Recommendations (section 2.1 of this report), Human Behavior (section 2.2), Health Disparities and Environmental Justice (section 2.3), and Air Cleaners (section 2.4). Appendix A lists all recommendations, including those not selected because they did not meet the EPA's requirements, with the priority assigned to each by the CAAAC working group that drafted this report. In addition to identifying and prioritizing recommendations from the NASEM report, the working group also reviewed and identified steps that could be taken to address several high priority indoor air "contaminants of concern," specifically, reactive oxygen species (ROS) and aldehydes. The working group's recommendations findings and recommendations relative to contaminants of concern can be found in Section 3.

Although peripheral to its charge, the CAAAC working group also considered whether there are aspects of indoor chemistry not addressed in the NASEM report that are of comparable importance as near-term research priorities. The following additional recommendations are the outcome of this process:

- Radon, which is mentioned numerous times in the NASEM report but not addressed in its recommendations, continues to be a significant health hazard in many regions. EPA radon programs should continue.
- Particulate matter, also highlighted multiple times in the NASEM report, is an increasingly problematic concern in the indoor environment. EPA should boost its efforts to quantify and lower indoor exposures.
- EPA should encourage more fundamentally oriented public-sector institutions to conduct surveys to determine which new chemicals are appearing in the indoor environment.

- EPA should encourage more fundamentally oriented public-sector institutions to investigate the health impacts of contaminants known to be in the indoor environment but for which insufficient health data are known as well as second order effects such as contaminant synergies.

CAAAC appreciates the opportunity to provide its views on the NASEM report and related issues to EPA and offers this report in the hope that it will provide useful input to EPA's planning efforts.

Appendix A: All Recommendations

Presented in order of appearance by chapter, with a priority ranking of 1 indicating the highest priority and a ranking of 5 indicating the lowest priority. Recommendations listed as "not selected" were considered beyond the scope of this working group's charge.

Item Number	Chapter	Recommendation	Average Priority Ranking
1	2	Prioritize acquisition of actionable data and research to link sources with exposures and understand impacts of mixtures on health.	1.0
2	2	Increase transparency in chemical applications/use in building materials to minimize time and effort needed to establish evidence of exposure and health risks.	2.0
3	2	Improve analytical methods and non-targeted approaches to support discovery. In the past, a number of chemicals of human health concern have been identified in indoor settings using targeted or screening methods.	Not selected
4	2	Develop and maintain harmonized chemical information databases.	Not selected
5	2	Expand research further into nonresidential settings and underrepresented countries and contexts.	5.0
6	3	Expand equilibrium and nonequilibrium (dynamic and steady-state) partitioning studies to include a larger variety of materials present in buildings.	Not selected
7	3	Examine the influence of environmental conditions and occupant activities on equilibrium and nonequilibrium partitioning and the influence of partitioning on contamination management.	Not selected
8	3	Develop a molecular-level understanding of partitioning among indoor reservoirs.	Not selected
9	3	Improve predictive models of equilibrium and nonequilibrium partitioning and compare them with observations from laboratory experiments and real-world, occupied buildings.	Not selected
10	3	Identify key species, materials, and partitioning phenomena that strongly influence exposure.	Not selected
11	4	Expand research into the chemistry associated with human occupancy, behavior, and activities, especially to identify processes that alter exposure to chemicals.	3.0

Item Number	Chapter	Recommendation	Average Priority Ranking
12	4	Investigate transformations of long-lived contaminants.	Not selected
13	4	Apply advanced instrumentation and analytical techniques to study chemistry taking place in a broader range of building types, including their air, contents, and surfaces.	Not selected
14	4	Broaden our understanding of chemistry taking place on and within the complex surface materials and interfaces present within buildings.	Not selected
15	4	Expand, improve, and integrate models across different timescales and spatial scales.	Not selected
16	5	Testing approaches need to be developed that consider both efficacy and byproduct formation in a representative range of real-world environments (*e.g.*, ultrafine particles, PM2.5, oxygenated VOCs including formaldehyde).	2.0
17	5	Developers of air-cleaning technologies need to recognize that many gas-phase molecules in indoor air partition with indoor surface reservoirs.	5.0
18	5	Controlled field experiments are necessary to better understand the fundamental chemistry of emerging air-cleaning technologies, as well as mold and smoke remediation schemes.	2.0
19	5	Given the recent public interest in indoor air quality, device manufacturers, researchers, and public health professionals need to communicate clearly to consumers about the efficacy and chemical consequences of different air-cleaning approaches.	1.5
20	6	Review current science of indoor chemistry to define gaps in current exposure assessment methods or data collection.	2.0
21	6	Develop more harmonized measures to characterize indoor exposure disparities.	2.0
22	6	Develop methodological and technological tools to make direct measurement of exposures easier, more convenient, and lower cost, especially to chemical mixtures, at scales that meaningfully improve the performance of exposure modeling and close gaps in understanding relationships between indoor environmental co-exposures to many chemicals and health outcomes, including persistent environmental health disparities.	2.0

Item Number	Chapter	Recommendation	Average Priority Ranking
23	6	Grow the network of data sources on human behaviors in indoor environments to become more representative of the U.S. population and establish criteria for standardization and harmonization across diverse sources, ranging from nationally distributed surveys by federal agencies, to market-based data, to individual- and community-based reporting.	Not selected
24	6	Deepen understanding of human behavior and time-activity patterns as they relate to indoor chemistry.	3.0
25	6	Improve understanding of first principles that mediate and govern exposure while continuing to build datasets that can provide empirical exposure model inputs.	5.0
26	6	Improve models through better integration of an understanding of human behavior.	3.0
27	6	Connect physical processes models to exposure and uptake models.	3.0
28	7	Recommendation 1: Researchers should further investigate the chemical composition of complex mixtures present indoors in a wide range of residential and nonresidential settings and how these mixtures impact chemical exposure and health.	3.0
29	7	Recommendation 2: Researchers should focus on understanding chemical transformations that occur indoors, using advanced analytical techniques to decipher the underlying fundamental reaction kinetics and mechanisms both in the laboratory and in indoor environments.	Not selected
30	7	Recommendation 3: Researchers should prioritize understanding the phase distribution of indoor chemicals between all indoor reservoirs and incorporate these findings into exposure models.	Not selected
31	7	Recommendation 4: All stakeholders should proactively engage across disciplines to further the development of knowledge on the fundamental aspects of complex indoor chemistry and its impact on indoor environmental quality, exposure assessment, and human health.	Not selected
32	7	Recommendation 5: Researchers who study toxicology and epidemiology and their funders should prioritize resources toward understanding indoor exposures to contaminants, including those of outdoor origin that undergo subsequent transformations indoors.	2.0

Item Number	Chapter	Recommendation	Average Priority Ranking
33	7	Recommendation 6: Researchers and their funders should devote resources to creating emissions inventories specific to building types and to identifying indoor transformations that impact outdoor air quality.	Not selected
34	7	Recommendation 7: Researchers and engineers should integrate indoor chemistry considerations into their building system design and mitigation approaches. This can be accomplished in different ways, including by consulting with indoor air scientists.	2.0
35	7	Recommendation 8: Given the challenges, complexity, knowledge gaps, and importance of indoor chemistry, federal agencies and others that fund research should make the study of indoor chemistry and its impact on indoor air quality and public health a national priority.	5.0
36	7	Recommendation 9: Researchers and their funders should invest in developing novel methods and chemoinformatic resources that increase our ability to identify and quantify the abundances of wide classes of indoor chemicals, both primary emissions and secondary chemical reaction products.	Not selected
37	7	Recommendation 10: Researchers measuring indoor environments should apply and develop new analytical tools that can probe the chemical complexity of gases, aerosols, and surfaces.	Not selected
38	7	Recommendation 11: Federal agencies should design and regularly implement an updated National Human Activity Patterns Survey. Federal and state agencies should add survey questions in existing surveys that capture people's activities in indoor environments as they relate to indoor chemistry and indoor chemical exposures.	3.0
39	7	Recommendation 12: Researchers should proactively engage in links that connect research to application throughout the indoor chemistry research process—for example, at the dissemination stage, by engaging with technical and standard-writing committees, presenting at conferences attended by practitioners, and disseminating the significance of research findings in social and mass media.	2.3
40	7	Recommendation 13: Researchers and practitioners should include environmental justice communities in the wide range of indoor environments they study and engage these communities in formulating research priorities and recommendations for future indoor air quality standards.	2.0

Item Number	Chapter	Recommendation	Average Priority Ranking
41	7	Recommendation 14: Funding agencies should support interdisciplinary research to investigate the impact of products and services on indoor chemistry, especially under realistic conditions. There is also a need to determine how occupant access to air quality data leads to behavior that influences indoor chemistry.	4.0
42	7	Conclusion 1: Standardized consensus test methods could enable potential certification programs for air-cleaning products and services. Such test methods could help regulators determine whether action on these products and services is warranted.	1.0
43	7	Recommendation 15: Researchers and their funders should prioritize understanding the health impacts from exposure to specific classes and mixtures of chemicals in a wide range of indoor settings. Such understanding is needed to inform any future standards, guidelines, or regulatory efforts.	2.7