# The State of Air Quality in the Union - 2025

**Foreword: The Air We Breathe – A National Imperative for 2025**

The quality of the air—both the ambient environment that envelops our communities and the atmosphere within our homes, schools, and workplaces—stands as a paramount national concern as we look towards 2025. Air pollution, often an invisible threat, exerts a pervasive influence on public health, economic vitality, and environmental equity. A striking illustration of this concern is the fact that individuals in the United States spend, on average, approximately 90% of their time indoors.[1] Within these enclosed spaces, concentrations of certain pollutants can frequently be two to five times higher than those typically found outdoors, underscoring the critical need to address air quality in both domains.[1]

This report aims to deliver a comprehensive, data-driven assessment of the current state of air quality across the United States, drawing upon the most recent information available, primarily focusing on data from 2023-2025 and reports published within this timeframe. It is intended to serve as an authoritative resource for understanding prevailing trends, emerging challenges, significant health implications, and the strategic pathways forward. The findings presented herein synthesize information from leading organizations such as the American Lung Association (ALA), the U.S. Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), the Centers for Disease Control and Prevention (CDC), and various independent research institutions.

## Part I: The Unseen Environment – America's Outdoor Air Quality

### Section 1.1: National Outdoor Air Quality Snapshot (2023-2025)

An examination of outdoor air quality in the United States reveals a complex picture, characterized by significant long-term improvements juxtaposed with recent, concerning setbacks. The American Lung Association's (ALA) 2025 “State of the Air” report, which analyzes data from 2021-2023 and was released in April 2025, indicates that nearly half of all Americans—approximately 156 million people or 46% of the population—reside in areas that received a failing grade for either ozone or particle pollution.[4] This represents a substantial increase of 25 million people breathing unhealthy air compared to the previous year's report and marks the highest number in the past decade.[5] This alarming escalation is largely attributed to the compounding effects of extreme heat and widespread wildfires.[4]

Despite these recent challenges, it is crucial to acknowledge the substantial historical progress made in improving the nation's air quality. Long-term data from the EPA, extending through 2022, demonstrate the efficacy of the Clean Air Act of 1970. Between 1970 and 2022, the combined emissions of the six common criteria pollutants dropped by a remarkable 78%.[8] More specifically, from 1990 to 2022, national average concentrations of ozone decreased by 22%, and annual PM2.5 (fine particulate matter) concentrations fell by 42% (from 2000).[8] This enduring progress in reducing emissions from traditional sources like industrial facilities and vehicles has yielded significant public health benefits. However, the recent surge in exposure to unhealthy air underscores a new reality: while regulatory efforts have been successful against conventional pollution sources, the nation is now grappling with intensified environmental challenges, particularly those exacerbated by climate change, which are beginning to erode some of these hard-won gains. This dynamic suggests that future air quality management strategies must evolve to more aggressively address the impacts of climate-driven events like wildfires and heatwaves, moving beyond a sole focus on traditional emission controls.

Focusing on key criteria pollutants, the ALA's 2025 report highlights specific concerns:

- **Ozone (Smog)**: Over 125 million people, or 37% of the U.S. population, lived in areas with unhealthy ozone levels. This is an increase of 24.6 million individuals compared to the prior year's report. Extreme heat and wildfires, especially during the summer of 2023, were significant contributors to this rise, with notable impacts in central states ranging from Minnesota to Texas.[4] Los Angeles continues to be a prominent hotspot for high ozone concentrations.[6]
- **Particle Pollution (PM2.5 - Soot)**:
    - *Short-Term Spikes*: A concerning 77.2 million people experienced unhealthy spikes in particle pollution, the highest number recorded in the 16 years of the report's history. While some western states observed slight improvements in the number and severity of these spikes, conditions worsened in the Midwest and Northeast.[4] The summer of 2023, heavily impacted by smoke from Canadian wildfires, witnessed the highest number of days with particle pollution reaching "unhealthy" (red) and "very unhealthy" (purple) levels in

the 26 years of ALA reporting.[4]
  - *Year-Round Levels*: Approximately 85 million people resided in counties that received a failing grade based on the national standard for year-round PM2.5 levels. This figure is the second-largest in the report's history, following the 90.7 million reported previously.[4]
- **Other Pollutants (NO2,SO2,CO)**: While the ALA report primarily focuses on ozone and particulate matter, EPA data indicate continued long-term national declines in other criteria pollutants. From 1990 to 2022, annual average nitrogen dioxide ($NO_2$) concentrations decreased by 60%, 1-hour sulfur dioxide ($SO_2$) concentrations by 90%, and 8-hour carbon monoxide (CO) concentrations by 81%.[8] However, localized issues persist, and these pollutants can contribute to the formation of secondary pollutants like ozone and particulate matter.

The geographic distribution of air pollution also presents a shifting landscape. While Western cities, particularly in California, have historically dominated and continue to appear on lists for the worst particle and ozone pollution, recent data indicate a troubling trend of worsening particle pollution in the Midwest and Northeast, alongside high ozone levels in central states.[4] This geographical shift is strongly linked to the long-range transport of wildfire smoke and the regional impacts of heatwaves—phenomena that are increasingly amplified by climate change. The Canadian wildfires of 2023, for instance, significantly degraded air quality in these eastern and midwestern regions.[6] This development implies that air pollution is no longer a challenge confined to historically polluted urban or industrial areas; climate change is effectively nationalizing, and even internationalizing, these threats. Regions that previously enjoyed relatively cleaner air are now finding themselves vulnerable, necessitating new approaches to monitoring, forecasting, and public health preparedness.

Table 1: State of Key Outdoor Air Pollutants in the US (ALA "State of the Air" 2025 Report, data 2021-2023)
Source: 4

| Pollutant | Number of People Living in Counties with Failing Grade | Change from Previous Year's Report (Number) | Key Contributing Factors Noted in Report | Number of People in Counties with Failing Grades for All Three Measures |
|---|---|---|---|---|
| Ozone | 125.1 million | +24.6 million | Extreme heat, Wildfires | 42.5 million |

| | | | | |
|---|---|---|---|---|
| Short-Term Particle Pollution (PM2.5) | 77.2 million | Highest in 16 years | Wildfires (incl. Canadian 2023), Wood-burning stoves, Industrial sources | 42.5 million |
| Year-Round Particle Pollution (PM2.5) | 85.0 million | Slight decrease (from 90.7 million) | Wildfires, Industrial emissions, Diesel engines, Wood-burning stoves | 42.5 million |

The regional analysis of most polluted and cleanest areas further illustrates these trends:

- **Most Polluted Areas**:
  - *Short-Term Particle Pollution*: Bakersfield-Delano, CA; Fairbanks-College, AK; and Eugene-Springfield, OR, are among the top-ranked cities.[4] Bakersfield has consistently topped this list for three consecutive years.[5]
  - *Year-Round Particle Pollution*: Bakersfield-Delano, CA; Visalia, CA; Fresno-Hanford-Corcoran, CA; Eugene-Springfield, OR; and Los Angeles-Long Beach, CA, are consistently among the most polluted.[4] California cities feature prominently in these rankings.
  - *Ozone Pollution*: Los Angeles, CA, persistently records the highest ozone pollution levels.[9] Other highly ozone-polluted metropolitan areas are predominantly located in California, Nevada, Arizona, New Mexico, and Colorado. Fairfield, Connecticut, stands out as an East Coast city also experiencing markedly high ozone levels, largely due to meteorological patterns concentrating regional traffic-related pollution.[11]
- **Cleanest Cities**: A stark indicator of the overall worsening of air quality across the nation is the diminishing number of cities that qualify as "cleanest" for all three measures (ozone, short-term PM2.5, and year-round PM2.5). In the ALA's 2025 report, only two cities—Bangor, Maine, and San Juan, Puerto Rico—achieved this distinction, a significant drop from five cities in the previous year's report.[4] This reduction underscores the pervasive nature of current air quality challenges.

Table 2: Top US Metropolitan Areas Most Affected by Specific Outdoor Air Pollutants (ALA "State of the Air" 2025 Report)

Source: 4

| **Pollution Type** | **Top Ranked Cities/Metropolitan Areas (Examples)** | **Primary Region(s)** |
|---|---|---|
| Most Polluted by Short-Term Particle Pollution | 1. Bakersfield-Delano, CA <br> 2. Fairbanks-College, AK <br> 3. Eugene-Springfield, OR (tied) | West |
| Most Polluted by Year-Round Particle Pollution | 1. Bakersfield-Delano, CA <br> 2. Visalia, CA <br> 3. Fresno-Hanford-Corcoran, CA <br> 4. Eugene-Springfield, OR <br> 5. Los Angeles-Long Beach, CA | West |
| Most Polluted by Ozone Pollution | 1. Los Angeles-Long Beach, CA <br> Other examples include: San Bernardino, CA; Riverside, CA; Phoenix, AZ; Dallas, TX; Fairfield, CT (East Coast outlier) [6] | West, Southwest, East |

## Section 1.2: Escalating Threats: Wildfires, Extreme Heat, and the Climate Feedback Loop

Recent years have unequivocally demonstrated that wildfires and extreme heat are no longer peripheral concerns but central drivers of air quality degradation in the United States. These phenomena, intensified by climate change, are creating a complex and dangerous feedback loop.

The dominance of wildfire smoke as an air pollutant has become increasingly apparent. The years 2023 and 2024 saw unprecedented wildfire activity, with vast smoke plumes frequently blanketing extensive areas of the U.S., including regions not historically accustomed to such events.[9] A particularly striking example occurred in June 2023, when wildfires in Quebec, Canada, sent massive plumes of smoke over the eastern U.S. NOAA scientists estimated that this event alone exposed more than 86 million people to levels of fine particulate pollution (PM2.5) exceeding federal health standards.[12] This single event dramatically illustrated the transboundary nature of wildfire smoke and its capacity to affect densely populated areas far from the source. Wildfire smoke is now recognized as a major, and in some areas dominant, contributor to PM2.5 pollution, actively eroding decades of air quality improvements. One study indicated that wildfire smoke has negated approximately a quarter of the air quality gains made since the year 2000 [9], while another assessment suggests it now accounts for up to half of all ambient PM2.5 in the Western U.S., a significant increase from less than 20% a decade ago.[13] The chemical nature of this smoke is highly complex, comprising primary pollutants like particulate matter, carbon monoxide, nitrogen oxides, and sulfur oxides, which then react in the atmosphere to form secondary pollutants such as ground-level ozone and organic aerosols.[14] Adding to the concern, smoke originating from wildfires that encroach on urban areas—burning homes, vehicles, and synthetic materials—can release an even more toxic and hazardous mix of pollutants.[14] This "wildland-urban interface" fire smoke presents new challenges for understanding and mitigating health risks. The pervasive and often unregulated nature of wildfire emissions presents a formidable challenge to traditional air quality management frameworks, which are primarily designed to control localized, ongoing sources. The increasing frequency and scale of these smoke events necessitate a shift towards strategies emphasizing improved forecasting, robust public health alert systems, community resilience measures such as clean air shelters, and enhanced building filtration, alongside long-term efforts in climate mitigation and sustainable forest management.

Extreme heat acts as a potent amplifier of air pollution. The year 2023 was officially the warmest in NOAA's 174-year climate record, with widespread and record-breaking heatwaves affecting various parts of the country.[12] These heatwaves create ideal meteorological conditions for the formation of ground-level ozone, or smog. Higher temperatures accelerate the photochemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the presence of sunlight, leading to increased ozone concentrations.[4] This phenomenon, often termed the "climate penalty," describes the deterioration of ozone air quality directly attributable to rising temperatures driven by climate change. It has the potential to halt or even reverse progress made through controlling precursor emissions, with California being a notable region where this effect is already being observed.[16] This implies that current strategies for ozone reduction, which focus on limiting NOx and VOC emissions, may become insufficient in a progressively warmer world. Air quality management plans will increasingly need to account for this temperature-driven component, potentially requiring even more stringent controls on precursor emissions or innovative strategies to counteract the effects of heat. Extreme heat can also exacerbate particle pollution by contributing to drier conditions that fuel wildfires and increase the suspension of dust.[10]

The interconnectedness of these factors creates a vicious cycle. Climate change leads to more frequent and intense wildfires and heatwaves. These extreme weather events, in turn, worsen air pollution. Furthermore, some of the air pollutants generated, such as black carbon from fires and ground-level ozone, are themselves climate forcers, meaning they contribute to further warming of the planet. This feedback loop underscores the urgent need for integrated strategies that address both climate change and air pollution simultaneously.

## Section 1.3: The Health Burden of Polluted Outdoor Air

The detrimental impact of polluted outdoor air on human health is well-documented and extensive. Air pollution stands as a major public health risk, with both short-term and long-term exposures contributing to a wide array of adverse health outcomes. Key pollutants such as fine particulate matter (PM2.5) and ground-level ozone are implicated in conditions ranging from premature death and respiratory illnesses to cardiovascular events, cancer, and impaired cognitive function.[4] In the United States, PM2.5 is responsible for the majority of health effects stemming from air pollution.[18] These minute particles can penetrate deep into the lungs and even enter the bloodstream, triggering systemic health issues.[10] Ozone, a powerful respiratory irritant, has effects often likened to a "sunburn of the lungs," causing inflammation and damage to lung tissue.[4]

Recent research continues to solidify and expand our understanding of these health links:

- **Respiratory Diseases**: Exposure to air pollution is consistently linked to the aggravation of existing conditions like asthma and chronic obstructive pulmonary disease (COPD), as well as the development of new cases of asthma and bronchitis. It can also lead to reduced lung function and an increased susceptibility to respiratory infections.[8] Notably, research published in 2023 specifically connected exposure to ozone and PM2.5 with observable, detrimental changes in the airways of children.[18]
- **Cardiovascular Diseases**: The cardiovascular system is highly vulnerable to air pollution. Exposure can trigger heart attacks and strokes, impair blood vessel function, and contribute to the development of hypertension.[6]
- **Cancer**: Various air pollutants are classified as carcinogens. PM2.5 exposure is associated with lung cancer, as is reliance on coal for energy generation.

Proximity to major roadways has been linked to an increased risk of breast cancer. Long-term exposure to PM2.5 and NO2 has been associated with increased risks of colorectal and prostate cancers, while occupational exposure to benzene, a component of gasoline, can cause leukemia.[8]

- **Neurological and Cognitive Impacts**: The brain is emerging as a significant target for air pollution's harmful effects.
  - In **children**, exposure to PM2.5 may alter the trajectory of developing brain size and is linked to cognitive and emotional problems later in life. Prenatal exposure to polycyclic aromatic hydrocarbons (PAHs) has been associated with ADHD symptoms.[18] Overall, air pollution can disrupt learning processes.[9]
  - In **adults and the elderly**, there is a growing body of evidence linking PM2.5 exposure to an increased risk of dementia, including Alzheimer's disease, and Parkinson's disease.[9] Further research suggests that components of wildfire smoke or other air pollutants may contribute to neurodegenerative diseases by inducing chemical changes that disrupt normal brain cell function.[24] This expanding understanding of air pollution's neurological toll suggests the overall health burden may be significantly underestimated if these impacts are not fully considered, reinforcing the need for stringent air quality standards.
- **Reproductive and Developmental Effects**: Air pollution poses significant risks during pregnancy and early development. Exposure to PM2.5 during pregnancy is linked to an increased risk of preterm birth, low birth weight, and potentially autism in offspring. It can also contribute to hypertensive disorders during pregnancy and an increased risk of postpartum depression.[6]
- **Other Health Issues**: Beyond these specific categories, air pollution is also associated with an increased risk of developing diabetes, obesity, and various immune system disorders.[18]

The health burden of air pollution is not distributed equally across the population. Certain groups are disproportionately affected:

- **Communities of Color**: These communities often face higher exposure to unhealthy air and are more likely to suffer serious health consequences. This disparity is rooted in systemic racism, historical segregation, and the disproportionate siting of pollution sources (such as highways and industrial facilities) near these neighborhoods.[4] The ALA's 2025 report found that a person of color is more than twice as likely as a white individual to live in a community receiving failing grades for all three major pollution measures (ozone, short-term PM, year-round PM); for Hispanic individuals, this likelihood is nearly three times greater.[4] This reality positions air pollution as a critical environmental justice issue, acting as a "threat multiplier" that exacerbates existing health inequities. These communities may also experience higher rates of underlying health conditions that increase their vulnerability, often linked to social determinants of health such as limited access to quality healthcare and nutritious food.[5]

- **Low-Income Communities**: Individuals with lower socioeconomic status frequently experience greater exposure due to factors like the location and quality of their housing and fewer resources available for mitigation measures.[24]
- **Children**: Due to their developing lungs and brains, higher breathing rates relative to their body size, and behaviors that increase exposure (e.g., playing outdoors), children are particularly vulnerable to the harmful effects of air pollution.[19]
- **Older Adults**: This demographic faces a higher risk for many pollution-related diseases, especially cardiovascular and neurodegenerative conditions.[18]
- **Individuals with Pre-existing Conditions**: Those with underlying health issues such as asthma, heart disease, or diabetes are more likely to experience severe effects from air pollution exposure.[5]

## Section 1.4: Governance and Progress: The Clean Air Act and EPA's Role

The framework for managing outdoor air quality in the United States is primarily built upon the Clean Air Act (CAA) and the regulatory actions of the U.S. Environmental Protection Agency (EPA). The CAA, first enacted in its modern form in 1970 and subsequently amended, has been instrumental in achieving significant reductions in air pollution across the country.[5] As noted earlier, EPA data show that the combined emissions of the six common (criteria) pollutants dropped by 78% between 1970 and 2022, a period during which the U.S. economy experienced substantial growth.[8] This demonstrates that environmental protection and economic progress can be compatible.

Under the CAA, the EPA is mandated to set National Ambient Air Quality Standards (NAAQS) for six criteria pollutants: particulate matter (PM), ground-level ozone, carbon monoxide (CO), sulfur dioxide (SO2), nitrogen dioxide (NO2), and lead. These standards are established to protect public health with an adequate margin of safety, and to protect public welfare (e.g., visibility, damage to animals, crops, vegetation, and buildings).[8]

A significant recent development in this regulatory landscape was the EPA's final rule in February 2024, which lowered the annual health-based standard for PM2.5 from 12 micrograms per cubic meter (µg/m3) to 9.0 µg/m3.[7] This decision was based on an updated review of scientific evidence linking PM2.5 exposure to premature death and serious cardiovascular impacts. The American Lung Association's 2025 "State of the

Air" report utilized this stricter standard in its grading system, contributing to the higher number of areas receiving failing grades.[7] However, this move has not been without contention. As of March 2025, reports indicated that the EPA was reconsidering this more stringent standard, citing potential economic and implementation challenges.[10] This situation highlights an ongoing tension between the imperative to protect public health based on the latest science and pressures related to economic costs and regulatory feasibility. The precarious state of such regulatory protections is a critical aspect of the overall air quality narrative; if the primary federal agency tasked with ensuring clean air faces challenges in implementing or defending science-based standards, or if it experiences diminished capacity due to funding or staffing cuts, the nation's ability to make further progress on air quality could be compromised. This is particularly concerning given the new and intensifying challenges posed by climate-exacerbated pollution events.

The EPA, in collaboration with state, local, and tribal air pollution control agencies, manages an extensive network of air quality monitors across the country.[4] This monitoring data is crucial for determining compliance with NAAQS, tracking trends, informing the public, and supporting research. However, significant gaps in this monitoring network persist. The ALA's 2025 report noted that out of 3,221 counties in the U.S., only 922 are equipped to monitor for at least one pollutant, meaning that over 72.8 million people live in counties where their local levels of ozone or particle pollution are not being officially monitored.[4] This "monitoring gap" implies that a substantial portion of the population may be unaware of their local air quality conditions, and health impacts in these unmonitored areas may be underestimated or unaddressed. As air quality becomes increasingly dynamic and less predictable due to factors like wildfires and extreme weather, comprehensive and widespread monitoring is more critical than ever. Addressing this gap may require expanding the existing network and strategically integrating data from emerging technologies like low-cost sensors.

The EPA also plays a vital role in public information and outreach. Resources such as AirNow.gov (which incorporates NOAA's smoke forecasts) and the interagency Fire and Smoke Map provide real-time air quality information to the public.[12] Air Quality Awareness Week, an annual event typically held in May (May 5-9 in 2025, with the theme "Stay Air Aware"), is a key initiative to educate the public about air quality issues and protective actions.[32]

Despite past successes and ongoing efforts, challenges remain. The American Lung Association's 2025 report explicitly calls for public support and defense of the EPA's mission and resources, citing concerns about potential staff and funding cuts and the risk of regulatory rollbacks that could undermine clean air protections.[4] The increasing impact of climate change, particularly through more frequent and intense wildfires and heatwaves, poses new and complex challenges to the existing regulatory framework, which was primarily designed to address more predictable, controllable sources of pollution.

# Part II: The Air Indoors – A Closer Look at Our Living, Working, and Learning Spaces

## Section 2.1: Understanding Indoor Air: Pollutants, Sources, and Pathways

The quality of the air within our buildings—where individuals in the U.S. spend approximately 90% of their time—is a critical, yet often overlooked, determinant of health and well-being.[1] Alarmingly, indoor concentrations of some pollutants frequently range from two to five times higher than typical outdoor levels, and in some instances, can be more than 100 times higher.[1] This stark reality underscores the importance of understanding the complex interplay of pollutants, their sources, and their pathways into and within our indoor environments.

A diverse array of pollutants can compromise indoor air quality (IAQ):

- **Particulate Matter (PM2.5,PM10)**: These particles originate from both outdoor infiltration (e.g., wildfire smoke, traffic pollution, industrial emissions) and indoor sources such as cooking (a major contributor to peak indoor PM2.5 concentrations), smoking, dust, pet dander, and the burning of candles or incense.[1]
- **Volatile Organic Compounds (VOCs)**: A broad class of chemicals emitted as gases from numerous household and office products. Common sources include paints, varnishes, adhesives, pressed wood products in furniture and cabinetry, cleaning supplies, personal care products (e.g., hairspray, perfumes), office equipment like printers and copiers, pesticides, and air fresheners.[1]
- **Carbon Monoxide (CO)**: A colorless, odorless gas produced by the incomplete combustion of fuels. Indoor sources include malfunctioning or improperly vented fuel-burning appliances such as furnaces, water heaters, gas stoves, and fireplaces, as well as infiltration from attached garages where vehicles are running.[1]
- **Nitrogen Dioxide (NO2)**: Another combustion byproduct, primarily from unvented or poorly vented gas stoves, ovens, and space heaters. Outdoor NO2

from traffic can also infiltrate indoors.[8]

- **Radon**: A naturally occurring radioactive gas that can seep into buildings from the underlying soil and rock. It is invisible, odorless, and a leading cause of lung cancer among non-smokers.[1]
- **Mold and Biological Agents**: These include molds, bacteria, viruses, dust mites, and pet dander. They thrive in environments with excess moisture, often resulting from water leaks, high humidity levels, or inadequate ventilation.[1]
- **Carbon Dioxide (CO2)**: Primarily exhaled by building occupants. While not typically considered toxic at levels usually found indoors, elevated CO2 concentrations are a key indicator of inadequate ventilation.[34]
- **Asbestos and Lead**: Found in older building materials, such as insulation (asbestos) or paint (lead). Disturbance of these materials can release harmful fibers or dust.[1]
- **Ozone (O3)**: Can infiltrate from outdoors or be generated indoors by certain types of air cleaning devices that are not designed properly or are misused.[1]

Pollutants enter and accumulate in indoor spaces through several pathways:

- **Outdoor-to-Indoor Transport**: Outdoor air pollutants readily infiltrate buildings through various openings such as windows and doors, cracks in the building envelope (walls, floors, ceilings), and via ventilation systems.[1] Wildfire smoke serves as a dramatic example of how severe outdoor pollution events can profoundly degrade indoor air quality over large regions.[13] Even when buildings are seemingly sealed, fine particles like PM2.5 from smoke can penetrate, leading to a false sense of security for occupants who may believe they are fully protected indoors. This infiltration reality means that public health advice during such events must extend beyond simply "staying indoors" to include active measures like using high-efficiency particulate air (HEPA) filters and creating designated "clean rooms."
- **Indoor Generation**: Many pollutants originate from sources located within the building itself. These include emissions from building materials and furnishings (off-gassing of VOCs), occupant activities (cooking, cleaning, smoking), and biological growth (mold).[1] This "chemical soup" generated indoors is complex, as pollutants can interact with each other; for example, ozone can react with VOCs from cleaning products to form other harmful substances like formaldehyde.

Several factors can exacerbate poor IAQ. Modern energy-efficient building construction, while beneficial for energy conservation, can sometimes lead to reduced natural ventilation if not coupled with adequate mechanical ventilation systems, thereby trapping internally generated pollutants.[1] The increased use of synthetic building materials, furnishings, personal care products, pesticides, and household cleaners also contributes a wider array of chemical emissions to the indoor environment.[1] Furthermore, hotter outdoor temperatures and higher humidity levels can promote the growth of mold and increase the off-gassing rates of some VOCs.[2]

Improving IAQ thus requires a dual focus: minimizing the entry of outdoor pollutants and actively managing or eliminating indoor sources. This necessitates greater awareness regarding the selection of low-VOC materials and safer consumer products, ensuring proper ventilation during activities like cooking, and considering regulations or standards for emissions from everyday items that contribute to the indoor pollutant burden.

Table 3: Common Indoor Air Pollutants: Key Sources and Primary Health Effects
Source: 1

| **Pollutant** | **Common Indoor Sources** | **Primary Health Effects** |
|---|---|---|
| Particulate Matter (PM2.5/PM10) | Cooking, smoking, burning candles/incense, dust, pet dander, infiltration of outdoor pollution (e.g., wildfire smoke, traffic) | Respiratory irritation, asthma attacks, bronchitis, reduced lung function, cardiovascular problems, potential cancer risk |
| Volatile Organic Compounds (VOCs) - General | Paints, adhesives, solvents, cleaning supplies, air fresheners, new furniture/carpets, office equipment (printers, copiers) | Eye, nose, and throat irritation; headaches; nausea; dizziness; damage to liver, kidney, central nervous system; some are carcinogens |
| Formaldehyde (a specific VOC) | Pressed wood products (plywood, particleboard, MDF), glues, fabrics, gas stoves, tobacco smoke | Eye, nose, throat irritation; coughing; wheezing; allergic reactions; potential cancer risk (known human carcinogen) |
| Benzene (a specific VOC) | Tobacco smoke, stored fuels, paint supplies, emissions from attached garages, gas stoves (even when off) | Drowsiness, dizziness, headaches, eye/skin/respiratory tract irritation; long-term: blood disorders, leukemia (known human carcinogen) |
| Carbon Monoxide (CO) | Malfunctioning/improperly | Flu-like symptoms, fatigue, |

| | | |
|---|---|---|
| | vented fuel-burning appliances (furnaces, gas stoves, water heaters, fireplaces), tobacco smoke, car exhaust from attached garages | headaches, dizziness, confusion, nausea; high levels can be fatal |
| Nitrogen Dioxide (NO2) | Gas stoves and ovens, unvented gas heaters, tobacco smoke, infiltration from outdoor sources (traffic) | Respiratory irritation, increased susceptibility to respiratory infections, aggravation of asthma and COPD |
| Radon | Seepage from soil and rock beneath buildings, well water | No immediate symptoms; long-term exposure is the second leading cause of lung cancer |
| Mold & Biological Agents | Damp or wet areas caused by leaks, high humidity, condensation; contaminated HVAC systems | Allergic reactions (sneezing, runny nose, skin rash), asthma attacks, eye/nose/throat irritation, respiratory infections |
| Carbon Dioxide (CO2) | Exhaled by building occupants | High levels indicate poor ventilation; can cause drowsiness, headaches, difficulty concentrating |

## Section 2.2: IAQ Across Key Environments

The challenges and characteristics of indoor air quality vary significantly depending on the type of environment. Homes, schools, and offices each present unique pollutant profiles, exposure patterns, and vulnerable populations.

Homes:
The home environment, intended as a sanctuary, can unfortunately harbor a range of air pollutants. Studies consistently identify cooking as a major source of indoor PM2.5 and VOCs, with peak PM2.5 concentrations during cooking events often exceeding 150 µg/m3.34 In inadequately ventilated bedrooms, carbon dioxide (CO2) levels can become significantly elevated overnight, indicating poor air exchange.34 Gas stoves, common in many households, are known sources of nitrogen dioxide (NO2) and the carcinogen benzene, even when not in use due to potential leaks.21

Disparities in housing types significantly influence IAQ. Multi-family housing units, often situated in urban areas or near busy roadways, typically experience higher exposure to outdoor air pollution that infiltrates indoors.[28] Within these smaller living spaces, indoor sources like smoking and cooking can have a more concentrated impact, exacerbated by potential air transfer between units and sometimes less effective ventilation systems compared to single-family homes.[28] Research suggests that conventional low-income multi-family housing may exhibit higher concentrations of PM2.5 and NO2 compared to newer "green" buildings, and public housing developments may be disproportionately located near external pollution sources.[28] This creates an "illusion of haven" for vulnerable housing, where the home itself becomes a significant source or amplifier of pollution. Factors such as poorer building quality, deferred maintenance, inadequate ventilation (e.g., non-functional exhaust fans), and reliance on less safe heating or cooling methods (like unfiltered evaporative coolers in hot, dry regions) are common in lower-income and multi-family settings.[13] These issues are strongly linked to socioeconomic status, as lower-income households often lack the resources to implement IAQ improvements like purchasing air purifiers, upgrading ventilation, or relocating to healthier housing.[13]

Socioeconomic and regional factors further compound these issues. Lower socioeconomic status (SES) households are frequently associated with poorer housing quality, less effective ventilation, higher occupant density, and greater exposure to indoor secondhand smoke.[2] A study focusing on patients with idiopathic pulmonary fibrosis found higher indoor PM2.5 concentrations during winter in multi-household dwellings, on lower floors, and in lower-priced housing units.[29] In hot, arid regions like California's San Joaquin Valley, evaporative coolers are a common and affordable cooling method in low-income homes; however, these systems can draw in significant amounts of outdoor pollution, including wildfire smoke, if not equipped with adequate filtration, posing a distinct climate justice challenge.[13] The home environment is also a primary location for exposure to wildfire-PM2.5 [38], and the FRESSCA study highlighted the difficulties in effectively filtering smoke from evaporative coolers in these vulnerable communities.[13] Consequently, IAQ in homes is a significant environmental justice issue, requiring policies and programs that prioritize vulnerable housing through subsidies for improvements, filtration, and education, as individual actions alone are often insufficient.

Schools:
Indoor air quality in K-12 schools profoundly impacts the health, cognitive performance, attendance, and overall well-being of both students and staff.22 A concerning statistic reveals that approximately 50% of K-12 students in the U.S. attend schools that lack established IAQ management plans.30 Common pollutants in school environments include VOCs from

cleaning supplies, art materials, and new furnishings; particulate matter from chalk dust and outdoor infiltration; elevated $CO_2$ levels from occupant respiration (indicating poor ventilation); various allergens; and airborne pathogens.22

The consequences of poor IAQ in educational settings are significant. High levels of indoor pollution and inadequate ventilation have been shown to negatively affect all nine domains of cognitive function crucial for learning and complex tasks.[22] Conversely, improvements in IAQ can lead to substantial boosts in cognitive test scores, with some studies suggesting a potential doubling of cognitive capacity.[22] Poor IAQ is also linked to reduced productivity, increased school absenteeism due to illness, exacerbation of asthma, and the facilitated spread of airborne diseases such as COVID-19, influenza, and measles.[22] There are also concerns about potential long-term impacts on healthy brain development and mental health in children exposed to chronic poor IAQ.[22]

This highlights an urgent need to bridge the "IAQ equity gap" in education. Students in low-income and Tribal communities are disproportionately likely to suffer the negative health and cognitive consequences of poor IAQ in their schools.[30] These schools often lack the financial resources for modern HVAC systems, necessary upgrades like MERV-13 filters, or comprehensive IAQ management programs. Given that children are inherently more vulnerable to air pollution, this disparity in school IAQ directly contributes to educational inequities. Ensuring healthy IAQ in all schools is therefore a fundamental equity issue, essential for providing a basic prerequisite for effective learning and safeguarding child health.

Recent research and initiatives are beginning to address these challenges. Researchers at Boston University School of Public Health have developed a novel, low-cost method using $CO_2$ sensors to estimate Air Exchange Rates (AER) in classrooms, revealing significant ventilation variability even within the same school building—a tool that could be particularly valuable for resource-limited schools.[37] The CDC's revised guidance from May 2023 recommends a minimum of 5 Air Changes per Hour (ACH) and the use of MERV-13 or better filters in schools.[42] Legislative efforts, such as H.R. 9131, the "Indoor Air Quality and Healthy Schools Act of 2024" (introduced in July 2024), aim to authorize a national program to support IAQ improvements in schools, including assessments and technical assistance.[43] Additionally, EPA funding supports partnerships like the one between the National School Boards Association (NSBA) and the Go Green Initiative (GGI) to improve IAQ in low-income and Tribal schools.[30] Research from programs like the Harvard Healthy Buildings Program continues to underscore the associations between classroom IAQ and student cognitive scores.[45] Future efforts must focus on targeted funding and technical assistance for underserved schools, integrating IAQ management into standard school infrastructure and operational practices.

Offices & Commercial Buildings:

In office and commercial settings, poor IAQ directly impacts employee productivity, cognitive function, and health, often leading to increased absenteeism.11 Furthermore, poor outdoor air quality can strain building HVAC systems by increasing the buildup of particulates, which reduces system efficiency, elevates energy consumption, and results in higher maintenance costs.11

The COVID-19 pandemic, coupled with the increasing frequency of wildfire smoke events, has significantly elevated the importance of IAQ in offices, transforming it from a mere comfort issue into a critical component of business continuity and employee well-being.[11] There is now a heightened expectation from employees for healthier indoor environments, making IAQ a factor in talent attraction and retention. Businesses are increasingly recognizing that investing in IAQ is an investment in human capital, operational resilience, and potentially, brand reputation, aligning with broader Environmental, Social, and Governance (ESG) considerations.[31]

Key IAQ management strategies for these environments include:

- **Ventilation**: Adhering to guidelines such as the CDC's recommendation of 5 ACH [42] and established ASHRAE ventilation standards (e.g., Standard 62.1).
- **Filtration**: The use of MERV-13 or higher efficiency filters is increasingly recommended, particularly during outdoor pollution events like wildfires.[11] HEPA filters may be used in targeted areas or within portable air cleaning units.
- **Source Control**: Managing emissions from office equipment (printers, copiers), cleaning supplies, and renovation materials; preventing the entry of outdoor pollutants from sources like loading docks or garages; and ensuring proper moisture control to prevent mold growth.[3]

Specific guidance for wildfire smoke preparedness is also emerging. The EPA published a "Best Practices Guide for Improving Indoor Air Quality in Commercial/Public Buildings During Wildland Fire Smoke Events" in May 2025, and ASHRAE Guideline 44-2024 provides further recommendations.[39] These guides emphasize HVAC enhancements, building weatherization to limit smoke intrusion, air monitoring, and the creation of designated cleaner air spaces within buildings.[39] Building Owners and Managers Association (BOMA) International also provides guidance, stressing a health-first approach, reliance on proven solutions, clear communication with occupants, and recommending MERV-13 filtration.[46] The Harvard Healthy Buildings Program actively conducts research on IAQ in workplaces, including studies on "forever chemicals" and optimal ventilation standards.[45]

## Section 2.3: The Health Toll of Contaminated Indoor Air

Exposure to contaminated indoor air can lead to a wide spectrum of health problems, ranging from immediate irritations to severe, chronic diseases. The primary causes of indoor air quality problems are indoor pollution sources that release gases or particles into the air.[1] Short-term effects can manifest after a single exposure or repeated exposures and commonly include irritation of the eyes, nose, and throat, as well as headaches, dizziness, and fatigue.[1] More serious health effects may emerge years after exposure has occurred or only after long or repeated periods of exposure. These can include debilitating or fatal conditions such as certain respiratory diseases, heart disease, and cancer.[1]

Specific links between common indoor pollutants and health effects are well-established:

- **Particulate Matter (PM2.5)** from indoor sources like cooking and smoking, or infiltrated from outdoors, contributes to respiratory issues and cardiovascular problems.[1]
- **Volatile Organic Compounds (VOCs)**, emitted from a wide array of products, can cause eye, nose, and throat irritation, headaches, nausea, and damage to the liver, kidneys, and central nervous system. Some VOCs, such as formaldehyde and benzene, are known human carcinogens.[1]
- **Carbon Monoxide (CO)**, if allowed to accumulate to high concentrations, can be lethal. At lower levels, it can cause flu-like symptoms, confusion, and impaired judgment.[1]
- **Nitrogen Dioxide (NO2)**, particularly from gas stoves, is a respiratory irritant linked to the development of asthma and an increased susceptibility to respiratory infections. Studies have specifically associated NO2 from gas stoves with an increased incidence of pediatric asthma.[8]
- **Radon** is the second leading cause of lung cancer in the United States, after smoking.[1]
- **Mold** exposure can trigger allergic reactions, asthma attacks, and other respiratory infections.[1]
- **Asbestos** fibers, if inhaled, can lead to lung cancer, mesothelioma, and asbestosis.[1]

The phenomenon known as **Sick Building Syndrome (SBS)** describes situations where building occupants experience acute health and comfort effects that appear to be linked to time spent in a building, but no specific illness or cause can be identified. Symptoms often include headaches, fatigue, difficulty concentrating, and irritation of the eyes, nose, and throat, and are frequently attributed to poor indoor air quality.[42]

Beyond these direct health effects, poor IAQ, characterized by high levels of CO2, VOCs, or PM2.5, has been demonstrably linked to declines in cognitive function, decision-making abilities, and overall productivity in both office workers and students.[11] This suggests a significant, though often underestimated, economic drain. While the direct healthcare costs associated with treating IAQ-related illnesses are substantial, the indirect economic impacts stemming from reduced productivity, impaired cognitive performance, and increased absenteeism represent a considerable burden on businesses and educational institutions.[11] For instance, poor IAQ leading to clogged HVAC filters can also increase energy consumption and maintenance expenses for building systems.[11] The growing market for IAQ products like air purifiers and advanced filters indicates a recognized value in mitigating these issues, but this often represents a reactive cost.[31] A comprehensive assessment of the state of IAQ should therefore highlight these economic dimensions, framing investments in better IAQ not merely as a health measure but as an economic strategy with potential returns through improved productivity, reduced healthcare expenditures, and lower operational costs.

The effects of poor IAQ are often more severe for vulnerable groups, including children, whose developing bodies are more susceptible; older adults, who may have diminished physiological reserves; and individuals with pre-existing health conditions like asthma or heart disease.[1]

## Section 2.4: IAQ Management

The approach to managing indoor air quality is undergoing a significant transformation, driven by increased public awareness, technological innovation, and a growing body of scientific evidence linking IAQ to health and productivity. The U.S. Indoor Air Quality Market reflects this shift, valued at USD 10.5 billion in 2024 and projected to expand to USD 12.9 billion by 2029, with a compound annual growth rate (CAGR) of 4.30%.[31] Key market drivers include increasingly supportive government regulations (though still limited for IAQ specifically), heightened consumer awareness of the necessity for IAQ products, and the tangible increase in indoor air pollution concerns.[31]

Technological advancements are at the forefront of this evolution:

- **Air Purification Technologies**: There is a burgeoning market for air purifiers, humidifiers, dehumidifiers, advanced ventilation systems, and sophisticated air filters. High-Efficiency Particulate Air (HEPA) filters, filters with high Minimum

Efficiency Reporting Values (MERV-13 and above), and activated carbon filters designed to remove VOCs and ozone are becoming more commonplace in residential, commercial, and institutional settings.[11] Nanotechnology is an emerging frontier in air purification, with the potential to trap or even destroy contaminants at a molecular level. An example is the Kronos Model 8 air disinfection device, which received FDA clearance in July 2024 and utilizes a patented High Voltage Field technology to remove airborne particles as small as 0.0146 microns.[31]
- **IAQ Sensing and Monitoring**: The development of more precise, efficient, and compact sensors utilizing advanced environmental sensing technology is revolutionizing IAQ monitoring.[31] The integration of the Internet of Things (IoT), Artificial Intelligence (AI), and Machine Learning (ML) into IAQ products is enabling smart, real-time monitoring and automated control systems.[31] Low-cost CO2 sensors, for instance, have been effectively used by researchers at Boston University School of Public Health to estimate ventilation rates in school classrooms, offering a practical tool for IAQ assessment.[37] Academic research is actively exploring novel sensor technologies, including the application of instructor-worker Large Language Model (LLM) systems for sophisticated air quality data analysis, as demonstrated in a case study of the Los Angeles wildfires of January 2025.[48] Conferences like the UC Davis Air Sensors International Conference (ASIC) 2024 highlight ongoing efforts in next-generation sensor development, data quality assurance, and community-based applications.[49] This "Smart IAQ" revolution holds immense promise for personalized and responsive air quality management but also presents challenges. The accuracy and reliability of low-cost sensors can vary, necessitating careful calibration and quality control.[49] Furthermore, the sheer volume of data generated requires sophisticated interpretation to provide actionable insights rather than just raw numbers. Ensuring equitable access to these advanced technologies and addressing potential data privacy concerns are also critical considerations.
- **Ventilation Strategies**: There is a renewed emphasis on optimizing building ventilation to dilute and remove indoor pollutants, with guidelines such as the CDC's recommendation of at least 5 Air Changes per Hour (ACH) for many indoor spaces gaining prominence.[42]

This evolving landscape is also shaped by updated guidelines and standards from various authoritative bodies:

- The **CDC's** May 2023 revised guidance for building ventilation, emphasizing ≥5 ACH and the use of MERV-13 or higher rated filters, is a key benchmark.[42] The CDC also advises a cautious approach towards new or emerging IAQ technologies, preferring those with demonstrated efficacy.[42]

- **ASHRAE** (formerly the American Society of Heating, Refrigerating and Air-Conditioning Engineers) provides detailed technical standards for ventilation (e.g., Standard 62.1) and filtration. Their Guideline 44-2024 specifically addresses the protection of building occupants from smoke during wildfire and prescribed burn events.[39]
- The **EPA** continues to rank IAQ among the top five environmental risks to public health.[31] While its direct regulatory authority over IAQ in non-federal buildings is limited, the agency provides extensive guidance for improving IAQ in homes, schools, and during wildfire smoke events.[1] The EPA's strengthening of the outdoor PM2.5 NAAQS in February 2024 to 9.0 µg/m3 also indirectly benefits IAQ by reducing outdoor pollutant infiltration.[31]
- The **World Health Organization (WHO)** has established IAQ guidelines and, in 2025, shared its Air Quality Standards database, which tracks national standards for key pollutants worldwide.[24]

Despite these advancements, challenges persist. The initial cost of IAQ products and a lack of standardization in some areas remain significant market restraints.[31] Critically, poor IAQ is largely unregulated by the federal government and many state governments, creating inconsistencies in protection across the nation.[31]

Table 4: Key Recommendations for Improving Indoor Air Quality in Various Settings
Source: 1

| Setting | Key Action Category | Examples / Targets | Key Guidance/Standard Source(s) |
|---|---|---|---|
| **Homes** | **Source Control** | Use low-VOC paints/materials, ensure proper appliance venting (esp. gas stoves), avoid smoking indoors, manage pet dander, store chemicals properly. | EPA, CDC |
| | **Ventilation** | Use kitchen/bath exhaust fans, open windows when outdoor air is clean, ensure adequate | EPA, ASHRAE |

| | | | |
|---|---|---|---|
| | | overall home ventilation. | |
| | **Filtration** | Use high-MERV filters in HVAC systems (MERV 13+ if system allows), use portable HEPA air cleaners in key rooms (bedrooms, main living areas). | EPA, ALA, CDC |
| | **Monitoring** | Install CO and smoke detectors, test for radon, consider PM2.5 or CO2 monitors for awareness. | EPA, CPSC |
| **Schools** | **Source Control** | Use low-emitting cleaning/art supplies, manage dust/allergens, ensure proper chemical storage in labs. | EPA, CDC |
| | **Ventilation** | Aim for ≥5 Air Changes per Hour (ACH), ensure HVAC systems are properly maintained and bringing in sufficient outdoor air. | CDC, ASHRAE (Std 62.1) |
| | **Filtration** | Install MERV-13 or higher filters in HVAC systems, use portable HEPA air cleaners in classrooms, especially for vulnerable students. | CDC, EPA, ASHRAE |
| | **Monitoring** | Monitor CO2 levels as | EPA, CDC (guidance) |

| | | | |
|---|---|---|---|
| | | an indicator of ventilation adequacy, consider PM2.5 monitoring, especially if near pollution sources or during smoke events. | |
| **Offices/Commercial Buildings** | **Source Control** | Manage emissions from office equipment, use low-VOC renovation materials, implement green cleaning policies, control vehicle exhaust near intakes. | EPA, BOMA |
| | **Ventilation** | Meet or exceed ASHRAE Standard 62.1 ventilation rates, aim for ≥5 ACH where feasible, increase outdoor air during high occupancy or pollution events. | ASHRAE, CDC |
| | **Filtration** | Use MERV-13 or higher filters in HVAC systems, consider enhanced filtration (e.g., HEPA) in specific zones or portable units. | ASHRAE, EPA, BOMA |
| | **Monitoring** | Implement IAQ monitoring for PM2.5, CO2, VOCs, temperature, humidity; integrate with Building Management Systems (BMS) for active control. | EPA (guidance), ASHRAE |

# Part III: Charting a Course for Cleaner Air – Integrated Strategies and Future Outlook

## Section 3.1: Policy and Legislative Horizons

The governance of air quality in the United States is a complex interplay of federal, state, and local actions, with an increasing recognition of the need for more cohesive strategies, particularly for indoor environments.

At the federal level, a significant legislative development is **H.R. 9131, the "Indoor Air Quality and Healthy Schools Act of 2024"**. Introduced on July 25, 2024, and referred to the House Committee on Energy and Commerce, this bill aims to authorize a national program dedicated to reducing health threats posed by indoor air contaminants.[43] Key provisions include conducting research, developing guidelines for specific indoor contaminants (initially targeting particulate matter, carbon monoxide, nitrogen dioxide, ozone, formaldehyde, and radon), studying the feasibility of a national IAQ index, providing technical and financial assistance for IAQ improvements, establishing voluntary healthy building certifications, and conducting a national assessment of IAQ in schools and childcare facilities.[43] The introduction of H.R. 9131 signals a growing federal acknowledgment that IAQ is a distinct public health issue requiring a more unified national approach, moving beyond the current fragmented landscape where IAQ in private and non-federal public buildings is largely unregulated at the federal level.[31]

Federal agencies continue to play crucial roles:

- The **EPA** sets National Ambient Air Quality Standards (NAAQS) for outdoor air, provides extensive IAQ guidance for various settings, and funds research and community projects.[1] The EPA's Science Advisory Board has consistently ranked IAQ among the top five environmental risks to public health, yet comprehensive federal regulation for IAQ in most buildings remains elusive.[31]
- The **CDC** issues influential IAQ guidelines, particularly concerning ventilation (e.g., the May 2023 update) and in response to public health threats like the COVID-19 pandemic and wildfire smoke.[19] The CDC's National Environmental Public Health Tracking Network is a valuable resource for linking environmental data, including air quality metrics, to health outcomes.[54]
- The **Consumer Product Safety Commission (CPSC)** addresses hazards related to consumer products that can impact IAQ. Its Strategic Plan for 2023–2026 emphasizes preventing hazardous products from reaching consumers, effectively

addressing those already in the marketplace, and communicating safety information.[56] A notable area of CPSC focus has been gas stoves, with the agency acknowledging health risks from their emissions (NO2, CO, PM).[35] While the CPSC Chair has stated there is no current plan to ban gas stoves, the agency continues to monitor associated health risks and has issued recalls for CO hazards.[21] This highlights a key intersection where consumer product safety directly influences indoor air pollution.

- The **Department of Housing and Urban Development (HUD)**, while not extensively featured in the provided materials for direct IAQ actions, plays a critical role in housing standards and addressing housing disparities, which are intrinsically linked to IAQ equity.[26]
- An international note of concern involves the **US State Department's** reported plans to discontinue air quality monitoring at 80 of its embassies. In many countries, these U.S. sensors are the only reliable source of local air quality data, and their removal could impede public health information globally.[24]

State and local governments often take the lead in IAQ initiatives due to the limited scope of federal regulation in this area.[51] The **Association of Air Pollution Control Agencies (AAPCA)**, in its 2025 "State Air Trends & Successes (StATS)" Report, showcases achievements by state and local agencies in reducing pollution, such as PM2.5 reductions in California's San Joaquin Valley and toxic air contaminant reductions in Louisville, Kentucky.[32] The report also notes that wildfires and miscellaneous sources have become the majority emitters of particulate matter in the U.S..[32] The **Model Clean Indoor Air Quality Act (MCIAA)** provides a legislative framework that states can adapt to implement IAQ measures tailored to their specific needs.[51] Public health campaigns, such as the EPA's annual Air Quality Awareness Week (May 5-9, 2025, with the theme "Stay Air Aware"), actively involve state, local, and tribal partners in raising awareness.[32] The Association of State and Territorial Health Officials (ASTHO) also highlights innovative IAQ programs at the state level.[51]

A significant portion of recent IAQ policy discussions and guidance appears to be "crisis-driven," spurred by major public health events like the COVID-19 pandemic and the escalating impacts of wildfire smoke.[39] The pandemic brought unprecedented attention to the airborne transmission of viruses indoors, leading to a surge in focus on ventilation and filtration, as reflected in the CDC's revised May 2023 ventilation guidance.[42] Similarly, the increasing frequency and intensity of wildfires have prompted new guidance from the EPA (May 2025 guide for commercial/public buildings) and ASHRAE (Guideline 44-2024) on protecting building occupants from smoke.[39] While these responses are vital, they are largely reactive. The challenge lies in leveraging the heightened awareness generated by these crises to implement more comprehensive, proactive, and foundational IAQ improvements, embedding good IAQ principles into standard building codes, design practices, and operational procedures, rather than treating them solely as emergency measures.

Internationally, the **WHO** plays a key role by establishing global air quality guidelines. Its 2025 Air Quality Standards database tracks national standards, and there is a global target endorsed by Ministries of Health to reduce the health impacts of air pollution by 50% by 2040, compared to 2015 levels.[24]

## Section 3.2: Technological Frontiers in Air Quality Improvement

The pursuit of cleaner air is being significantly advanced by a wave of technological innovation, spanning advanced monitoring and sensing capabilities to breakthrough air purification methods.

Advanced Air Monitoring and Sensing:
The ability to accurately measure and understand air pollution is fundamental to managing it. Recent years have seen remarkable progress in this domain:

- **Low-Cost Sensors (LCS)**: There has been a proliferation of LCS, which offer the potential to characterize air quality with much finer spatial and temporal resolution than traditional, expensive regulatory monitors.[49] These sensors can empower communities with local air quality data and could reshape regulatory approaches. However, challenges related to data quality, calibration, standardization, and interpretation remain critical areas of focus.[49]
- **Mobile Sensors**: The integration of air sensors into mobile platforms (e.g., vehicles, personal devices) is revolutionizing community-based data collection and engagement, allowing for dynamic mapping of pollution hotspots.[49]
- **Nanosensors**: Research into nanosensor technology is showing promise for highly sensitive and selective detection of pollutants. The EPA's Science to Achieve Results (STAR) program has funded research into developing nanosensors for detecting, monitoring, and even degrading pollutants like Per- and Polyfluoroalkyl Substances (PFAS) in water sources.[59] While currently focused on water, this indicates the direction of sensor technology development, leveraging the unique properties of nanomaterials for improved efficiency and reduced cost.[31]
- **AI and LLMs in Air Quality Analysis**: Artificial intelligence and machine learning are being increasingly applied to air quality forecasting and data analysis.[48] For example, researchers are developing instructor-worker Large Language Model (LLM) systems integrated with Geographic Information Systems (GIS) for

analyzing air quality data during events like wildfires and for generating policy recommendations, as demonstrated in a case study of the January 2025 Los Angeles wildfires.[48]

- **Next-Generation Air Quality Models**: Air quality modeling is also advancing, with new approaches that utilize adaptive mesh or variable-resolution grids. These models allow for multi-scale simulations down to very fine resolutions (hectometer level), balancing accuracy with computational efficiency. The use of Graphics Processing Units (GPUs) for hardware acceleration and the integration of machine learning methods are further enhancing model performance and prediction accuracy.[60]

The rapid increase in data from these advanced sensor networks and models presents both opportunities and challenges. While this "data deluge" can provide unprecedented insights, the critical task is shifting from mere data acquisition to effective data interpretation, validation, and translation into actionable intelligence that can be used by diverse end-users, from individual citizens to policymakers.[48] This requires investment in data science tools for quality assurance and control (QA/QC), development of standardized communication protocols, support for community science initiatives, and training in data interpretation.

Breakthroughs in Air Purification:
Alongside better monitoring, technologies for cleaning the air are also evolving:

- **Advanced Filtration Materials**: Development continues on high-efficiency filters, such as HEPA and high-MERV rated filters, which are crucial for removing particulate matter. Specialized media, like activated carbon, are used to target gaseous pollutants such as VOCs and ozone.[11]
- **Nanotechnology in Purification**: Beyond sensing, nanotechnology holds potential for actively purifying air by trapping or destroying indoor contaminants at a molecular level.[31] An example is the Kronos Model 8 air disinfection device, which received FDA 510(k) clearance in July 2024. This device employs a patented High Voltage Field technology to remove airborne contaminants and allergens down to 0.0146 microns, a size significantly smaller than what traditional HEPA filters can capture.[31] This points towards a future where air purification moves beyond simple mechanical capture to more active chemical or photocatalytic destruction of pollutants.
- **Novel Mitigation Techniques**: While primarily focused on soil and water remediation, research into innovative techniques like using biochars to prevent PFAS uptake by plants demonstrates a broader trend towards preventing pollution at its source or intercepting pollutants before they cause widespread exposure.[59] For IAQ, this translates to a greater emphasis on selecting low-emitting building

materials, designing consumer products that do not off-gas harmful chemicals, and improving control over combustion processes.

The **EPA plays a significant role in fostering such innovation** through programs like its STAR program, which funds extramural research at academic and non-profit institutions on high-priority environmental and public health issues, including air pollution.[53] Specific STAR grant solicitations have targeted the development of nanosensor technology for PFAS.[59] The EPA's Small Business Innovation Research (SBIR) program also supports small businesses in developing and commercializing innovative environmental technologies.[59] Furthermore, the Inflation Reduction Act (IRA) of 2022 allocated over $11 billion to the EPA's Office of Air and Radiation to support new and existing programs aimed at securing clean air and a safe climate, including through grant funding.[52]

## Section 3.3: Empowering Action: Public Awareness, Education, and Community Engagement

Achieving cleaner air requires not only robust policies and advanced technologies but also an informed and engaged public. Empowering individuals and communities with accessible data, actionable knowledge, and opportunities for participation is crucial for driving meaningful change.

The Importance of Accessible Data and Communication:
Effectively communicating air quality information is paramount for enabling both personal protective actions and broader policy advocacy.49 This involves translating complex scientific data into clear, understandable, and relevant messages tailored to diverse audiences. Key federal resources facilitating this include the EPA's AirNow website and the interagency Fire and Smoke Map, which provide real-time air quality data and forecasts, including information on wildfire smoke.7 The EPA's annual Air Quality Awareness Week serves as a focused public outreach campaign, often in collaboration with state, local, and tribal partners.32 At the CDC, the National Environmental Public Health Tracking Network offers valuable data and tools to help communities understand the connections between environmental exposures, like air pollution, and specific health outcomes.54
Public Health Campaigns and Resources:
Numerous organizations contribute to raising public awareness. The American Lung Association's annual "State of the Air" report is a highly visible and influential publication that grades communities on air pollution levels and highlights national trends.4 Health professional organizations like ASTHO often feature state-level public health initiatives and innovations related to air quality.51 Guidance documents from the EPA and CDC on improving IAQ in homes and schools, and on protective measures during wildfire events, provide practical advice for the public.1

Community Engagement and Environmental Justice:
A critical aspect of empowering action is ensuring that efforts reach and resonate with all segments of the population, particularly vulnerable and historically marginalized communities. This means actively seeking to understand the unique needs and concerns of these communities and tailoring communication and outreach accordingly.56 Initiatives such as EPA funding for IAQ improvements in low-income and Tribal schools represent steps in this direction.30 Research is also exploring models for community-centric data collection using mobile sensors and fostering community ownership and use of air quality data, which can empower local advocacy and action.49 Addressing the stark disparities in air pollution exposure and related health impacts remains a central tenet of environmental justice.4
Despite the increasing availability of data and awareness campaigns, a significant "last mile" challenge persists in translating this information into consistent, widespread protective behaviors and equitable policy action.[13] Barriers to action can include the cost of mitigation measures (e.g., air purifiers, home remediation), confusion over complex information, a lack of agency (especially for renters or those in multi-family housing with limited control over building systems), and an underestimation of personal risk, particularly from chronic, low-level exposures.[13] Vulnerable communities often face the most significant hurdles. Therefore, public health strategies must evolve beyond simple information dissemination to incorporate behavioral science principles, address socioeconomic barriers through measures like subsidies for IAQ improvements, provide clear and culturally appropriate guidance, and support community-led initiatives with trusted local messengers.

Individual and Collective Actions:
Empowerment also involves highlighting the actions that individuals and communities can take:

- **For Outdoor Air Quality**: Reducing personal contributions to emissions (e.g., through transportation choices like using public transit, walking, cycling, or adopting electric vehicles), conserving energy, and advocating for stronger local, state, and federal clean air policies.
- **For Indoor Air Quality**: Implementing source control measures (e.g., choosing low-VOC products, ensuring proper ventilation when using gas stoves or engaging in other polluting activities), maintaining adequate ventilation, using appropriate air cleaners and high-efficiency HVAC filters, controlling indoor moisture to prevent mold, testing homes for radon, and avoiding indoor smoking.[1]

# A Unified Vision for Healthy Air in 2025 and Beyond

The state of air quality in the United States heading into 2025 presents a complex and urgent challenge. This report has synthesized recent data and research, revealing a dual reality: while long-term efforts have yielded significant improvements in controlling some traditional outdoor air pollutants, these gains are increasingly threatened by climate change-driven events such as intensified wildfires and extreme heat. Concurrently, indoor air quality remains a pervasive and often underestimated health concern, with a multitude of pollutant sources within our homes, schools, and workplaces, compounded by the infiltration of outdoor contaminants. A consistent and troubling theme across both domains is the disproportionate burden of exposure and adverse health effects borne by vulnerable populations, including communities of color, low-income households, children, older adults, and individuals with pre-existing health conditions.

The path towards healthier air for all Americans requires a multi-faceted, collaborative, and sustained commitment. Key actions are needed across various sectors:

- **Policymakers** at federal, state, and local levels must prioritize the strengthening and enforcement of science-based air quality standards for both outdoor and indoor environments. This includes investing in comprehensive monitoring networks, supporting climate mitigation and adaptation efforts that directly benefit air quality, and ensuring environmental justice by targeting resources and interventions to overburdened communities. Legislative initiatives like H.R. 9131, aimed at establishing a national framework for IAQ, particularly in schools, should be robustly supported and funded.
- **Industry** has a critical role in innovating for cleaner technologies and products. This involves designing and manufacturing low-emitting materials, safer consumer goods, and more effective and accessible air filtration and ventilation solutions. Businesses must also adopt sustainable practices and take greater responsibility for their emissions that impact both outdoor and indoor air.
- The **Research Community** must continue to advance our understanding of air pollution's complex health impacts, particularly emerging concerns like neurological effects and the interactive effects of multiple pollutants. Ongoing development of new monitoring technologies, advanced purification methods, and effective communication strategies for translating research into public action is essential.
- **Healthcare Professionals** are on the front lines of addressing the health consequences of air pollution. They can play a vital role in educating patients about air quality risks and protective measures, advocating for policies that protect public health, and recognizing the environmental triggers of illness.
- **Educators and School Administrators** have a responsibility to prioritize healthy indoor air quality in learning environments. This includes developing and

implementing IAQ management plans, investing in ventilation and filtration upgrades, and incorporating IAQ education into curricula.

- **Building Owners and Managers** must implement and maintain best practices for ventilation, filtration, and source control in commercial, public, and residential buildings, recognizing IAQ as a fundamental component of a healthy and productive environment.
- **Communities and Individuals** are crucial agents of change. Staying informed about local air quality, taking personal protective actions when necessary, advocating for cleaner air in their communities, and making conscious consumer choices can collectively contribute to significant improvements.

Achieving a future with healthy air is not merely an environmental goal; it is fundamental to public health, social equity, and economic prosperity. The challenges outlined in this report are substantial, but they are not insurmountable. Through a unified vision and concerted action that integrates public health imperatives, environmental protection, technological innovation, and a commitment to social justice, a healthier and more breathable future for all Americans is attainable.

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