The cost of clean air: Global disparities in reducing indoor wildfire-related $PM_{2.5}$ exposure

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Using air purifiers to reduce indoor exposure to wildfire-related $PM_{2.5}$ is effective but costly, placing a disproportionately higher financial burden on low-income countries.

THE GROWING IMPACT OF WILDFIRES ON INDOOR AIR QUALITY

Wildfires are increasing in both frequency and severity worldwide, releasing large amounts of air pollutants and posing health risks to the global population (*1*, *2*). On average, wildfire smoke made up about 6.1% of the total fine particulate matter ($PM_{2.5}$) worldwide each year (*1*). Exposure to wildfire smoke is associated with increased all-cause mortality and respiratory morbidity, including asthma exacerbation and chronic obstructive pulmonary disease (COPD). Both toxicological and epidemiological studies suggest that $PM_{2.5}$ from wildfires is more harmful than ambient $PM_{2.5}$ from other sources (*3*, *4*). Therefore, it is important to protect public health from wildfire smoke exposure.

During wildfires, people are often advised to shelter indoors and keep windows and doors closed. Outdoor $PM_{2.5}$, including wildfire-related $PM_{2.5}$, however, can still infiltrate indoors, as no building is completely airtight. While previous research has primarily focused on outdoor exposure, indoor exposure to wildfire-related $PM_{2.5}$ is a critical, yet often overlooked and understudied, issue. One recent study found that even with mitigation measures such as closing doors and windows and using filtration systems, indoor $PM_{2.5}$ concentrations on fire days can be nearly three times higher than on non-fire days (*5*). Understanding the impact of wildfires on indoor $PM_{2.5}$ levels is critical to better protect public health.

GLOBAL COSTS AND DISPARITIES IN REDUCING INDOOR WILDFIRE-$PM_{2.5}$

In this issue of *Science Advances*, Han *et al.* (*6*) present a global assessment of indoor exposure to wildfire-related $PM_{2.5}$ (referred to as fire-$PM_{2.5}$ in the article) over the past two decades. They found that from 2003 to 2022, more than 1 billion people worldwide were exposed to at least 1 day per year of substantial indoor fire-$PM_{2.5}$, with the majority of these exposures occurring in Africa, Asia, and South America. Indoor fire-$PM_{2.5}$ concentrations varied by region, with the highest level (0.83 μg/m^3) observed in Africa. South America had the highest proportion, with fire-$PM_{2.5}$ making up 5.0% of all indoor $PM_{2.5}$ sources. These findings highlight the urgent need to reduce indoor fire-$PM_{2.5}$ levels, especially during wildfire events.

Fortunately, indoor exposure to fire-$PM_{2.5}$ can be mitigated by using air purifiers equipped with high-efficiency particulate air (HEPA) filters (*7*). Their use, however, comes with substantial costs. Han *et al.* (*6*) estimated that the global cost of using air purifiers, including the purchase price, filter replacement cost, and electricity consumption, to keep indoor $PM_{2.5}$ concentrations below 5 μg/m^3—the annual limit recommended by the WHO (*8*)—could exceed $4 trillion USD per year. Of this, $69 billion was attributable to reducing fire-$PM_{2.5}$. The western coast of North America and northern Asia faced the highest total cost, while Africa bore the highest per capita cost. These findings highlight the financial burden many regions face to improve indoor air quality.

After accounting for per capita gross national income (GNI), Han *et al.* (*6*) further highlighted a key disparity: while the need to reduce indoor exposure to fire-$PM_{2.5}$ is global, the financial burden is not equitably distributed. Regions such as West Africa, Central Africa, and South Asia face the highest costs relative to their GNI. Low-income countries, in particular, bear nearly twice the cost of fire-$PM_{2.5}$ mitigation compared to high-income countries (Fig. 1), resulting in an even heavier burden relative to their GNI. All of the top 10 countries with the highest indoor fire-$PM_{2.5}$ concentrations were low- and middle-income countries (LMICs). Moreover, six of them also ranked among the top 10 in terms of fire-$PM_{2.5}$ mitigation costs as a proportion of GNI. These findings underscore the unequal financial burden placed on residents of low-income countries in efforts to reduce indoor exposure to fire-$PM_{2.5}$.

WHAT'S NEXT

As wildfires continue to intensify due to climate change (*9*), reducing indoor exposure to wildfire smoke has become a pressing global issue that goes beyond individual action and requires cross-disciplinary collaboration to inform comprehensive, policy-driven solutions. Building on the findings of Han *et al.* (*6*), future research should prioritize the following areas:

First, comprehensive exposure and health impact assessments are needed to quantify the effects of indoor exposure to fire-$PM_{2.5}$ including outcomes such as respiratory diseases, cardiovascular conditions, and overall mortality. During wildfire events, emissions from indoor sources such as cooking may also increase, as people tend to spend more time indoors and use gas appliances more frequently. Therefore, further research is warranted to investigate the combined health effects of indoor air pollution from all sources during wildfires.

Second, localized data and real-world validation are needed to test model assumptions. For example, building age is an important factor, as studies have shown that older buildings tend to have higher infiltration rates (*10*), allowing more outdoor $PM_{2.5}$ to

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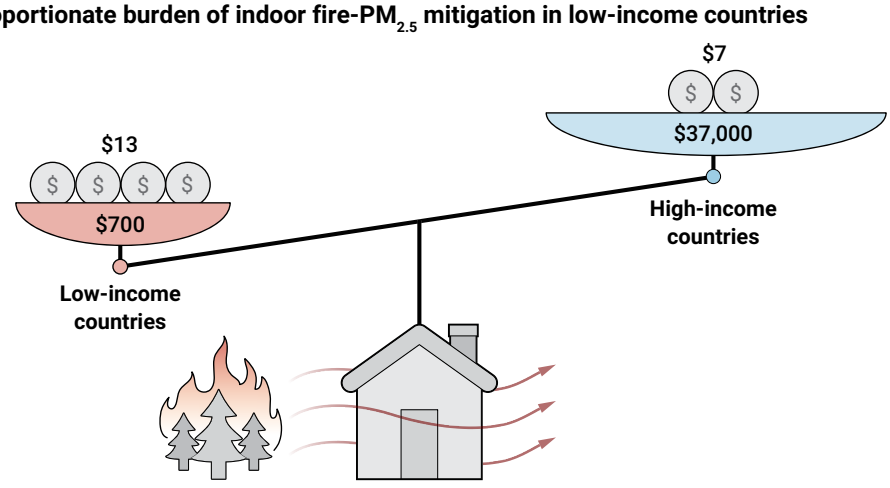

Fig. 1. Comparison of the per capita costs for reducing indoor exposure to fire-$PM_{2.5}$ between low-income and high-income countries. The number of coins symbolizes the cost of indoor fire-$PM_{2.5}$ mitigation, while the scale tray size indicates the gross national income levels in low- and high-income countries. Illustration credit: Ashley Mastin/*Science Advances*.

penetrate indoors. Future research should also explore a broader range of mitigation strategies beyond the use of air purifiers. These could include ventilation improvements and government-led initiatives to upgrade building infrastructure.

Third, understanding how public perception of risk influences behavior is another key area that could help address the socioeconomic disparities highlighted by Han *et al.* (*6*). People's decisions to take protective action depend on their awareness of risks, trust in information sources, and access to reliable guidance. Disparities in awareness and access to timely, accurate information may leave vulnerable populations less prepared to respond effectively. Future research should investigate these gaps to inform targeted educational campaigns and interventions.

Finally, future research should examine the role and effectiveness of government intervention programs and financial assistance policies aimed at reducing indoor exposure to fire-$PM_{2.5}$ and alleviating the financial burden of air purification, particularly for socioeconomically vulnerable populations. Evidence-based insights from such studies can inform the development of policy solutions to improve indoor air quality and protect public health in regions increasingly affected by wildfires.

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