Science Bulletin 69 (2024) 1161–1164

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

News & Views

The burden of disease due to indoor air pollution and why we need to know about it

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Ask a scientist from basically any area of science what they think about the immense scientific complexity of indoor air and its impacts, and they seem perplexed. Complexity of black holes—yes, complexity of the human genome—yes, but of indoor air? To scientists who investigate indoor air it is incomprehensible that this area of science attracts so little interest from the broader scientific community, the public, and frankly, anyone.

Indoors is where most contemporary people spend over 90% of their lives [1,2] breathing indoor air on average 12 times a minute. It keeps us alive. But it can also poison us and make us sick. Slowly, day by day, month by month, or year by year, until we are diagnosed with life-threatening cardiovascular disease, suffer a stroke, or develop cancer. We never know for sure if it was the impact of indoor air that caused it. Only through epidemiological studies are we able to attribute these health effects to indoor air quality, or rather, to indoor air pollution, on a population scale.

Indoor air pollution is often invisible and undetected by our olfactory sensors, but this is not the only reason for dismissing it as an interesting scientific topic; many areas of invisible, nanoscale science are hot topics. Maybe we do not think much about indoor air because of the long lag between cause and effect, so that we never know if it was the indoor air that made us sick. Or perhaps the perceived safety of our shelters, homes, offices or classrooms makes us blind to their dangers?

So what makes indoor air science so complex? It is the presence of thousands of pollutants in gaseous and particulate phases, which interact with each other through a myriad of physicochemical reactions [3–5]. It is also the presence of a rich biome of viruses, bacteria, and fungi [6,7]. These pathogens often thrive in indoor environments if the building design, its engineering, and the way we operate the whole system provide them with favourable conditions [8]. These pollutants and biological menageries come from all anthropogenic and natural sources that are outside, from sources that we bring or generate inside, and from us—humans are the main source of indoor airborne bacteria and viruses.

Given that every indoor environment is unique, does this mean that every environment should be a subject of scientific study? It may be considered utopia if this were really what we had to do, considering the billions of different indoor environments around the world. However, one of the biggest current scientific challenges is to use the relatively sparse data we have about different types of indoor environments to develop a generalised understanding of the science of indoor air and the impact of indoor air pollution on inhabitants. The lack of data is a big problem, precisely because neither scientists nor the research funding bodies consider the indoor environment to be a particularly important topic.

Generalisation means a general understanding of not only the emissions and mechanisms of processes taking place indoors, but also the emission rates and concentration levels of pollutants in different types of environments. This information is not just to satisfy scientific curiosity; it is to help understand the impact of indoor air pollution on humans—the invisible, unappreciated risk we potentially face 90% of the time, when we are indoors.

In this context, the Chinese Burden of Disease Attributable to Indoor Air Pollutants (CBD–IAP) project, launched in 2017, is a shining star. A major achievement of the project was to comprehensively estimate and rank the burden of disease (BOD) and financial costs attributable to specific residential IAPs at national and provincial level in China from 2000 to 2017 [9]. A team of researchers set out to evaluate through a systematic review and *meta*-analysis, 23 significant and robust exposure–response relationships of various IAPs with multiple health outcomes, including cardiovascular diseases, lung cancer, and asthma. The annual exposure levels of specific IAPs in residences in the 31 provinces, municipalities, or autonomous regions of Chinese mainland between 2000 and 2017 were then evaluated using systematic reviews, the infiltration factor method for outdoor-originated IAPs, and a spatiotemporal Gaussian process regression model for indoor-originated IAPs. Using the population attributable fraction (PAF) method, the attributable disability-adjusted life years (DALYs) of specific IAPs were further estimated at both national and provincial levels in China, and the corresponding financial costs were estimated using an adapted human capital approach.

BOD is a common indicator to provide a quantitative assessment of environmental health impacts, and is usually calculated using DALYs. Several large studies were conducted worldwide on

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https://doi.org/10.1016/j.scib.2024.02.031

the BOD attributable to IAPs. The first was the Word Health Organization (WHO) project on environmental BOD in Europe (EBoDE) for six European countries in 2009 [10], which included five residential IAPs (benzene, dioxins, second-hand smoke, formaldehyde, and radon). The chronic health effects of 69 IAPs in US residences in 2012 were estimated by Logue et al. [11]. However, the study used toxicological data from animal testing to estimate the attributable burden of most IAPs. Several years later the HealthVent study was conducted for 26 European countries [12], and included indoor residential $PM_{2.5}$ (particulate matter < 2.5 μm), carbon monoxide (CO), and indoor dampness. Finally, the Global Burden of Disease Study 2019 (GBD) assessed the BOD of 87 risk factors from 1990 to 2019 in 204 countries and territories based on PAF [13]. Only $PM_{2.5}$ from solid fuels and radon were considered as residential IAPs. Formaldehyde and benzene were only taken into account for occupational exposure.

Although the previous studies provided important evaluation methods for estimating the disease burden of IAPs, these studies mainly focused on the health impacts of IAPs in developed countries. China, which is among the largest developing countries, lacked systematic assessments of the BOD of IAPs. It was hypothesised that the exposure levels, attributable BODs, and corresponding rankings of IAPs in China may be quite different from those in developed countries.

The focus on China was particularly interesting. Over the past few decades, China has experienced rapid urbanisation and economic growth that has led to severe outdoor air pollution problems. To address this problem, China issued the Air Pollution Prevention and Control Action Plan in 2013 [14] with stringent control measures legislated by law, including outdoor air pollution standards. This resulted in a remarkable reduction in outdoor air pollution, particularly in $PM_{2.5}$, whose emissions were a particular focus of control measures, leading to a substantial decrease in concentrations and population exposure throughout China [15]. However, as in other countries, indoor air pollution and related adverse health impacts have received much less attention in China. Without quantitative evaluations, the degree of the problem remained unknown.

It is interesting to note what motivated the study's principal investigator Yinping Zhang and the study's scientific advisor Haidong Kan [9] to carry out this work. Both participated in a WHO Consultation: Evidence Available for the Future Update of the WHO Global Air Quality Guidelines (AQGs) in 2015, in Bonn, Germany. During the meeting Zhang pondered why more attention was devoted by the group to outdoor air pollutants than IAPs. The reason was obvious—there was very little data on the BOD of IAPs. Zhang and Kan thought this was extraordinary, considering the importance of indoor air, and decided to undertake work to address this knowledge gap. They secured a grant from the Ministry of Science and Technology of China in 2017 and established an interdisciplinary team of more than 30 researchers to participate in the study, which 8 years later led to important findings [9]. The team found that from 2000 to 2017, the BOD attributable to IAPs in China decreased from 4620 DALYs per 100,000 to 3700 DALYs per 100,000, by an average of 20%. However, in 2017, DALYs attributable to IAPs still accounted for 14.1% of the total DALYs in China and ranked third among all risk factors, after tobacco and high blood pressure. The corresponding financial costs due to exposure to IAPs reached 2880 billion CNY (~411 billion USD) in 2017 and accounted for 3.45% of China's gross domestic product. These are extremely high costs for Chinese society to pay for indoor air pollution.

The study also provided rankings of ten specific IAPs in China in 2017 (Fig. 1a), which were, from highest to lowest, $PM_{2.5}$, CO, radon, benzene, nitrogen dioxide, ozone, sulfur dioxide, formaldehyde, toluene, and p-dichlorobenzene. Among all targeted IAPs, $PM_{2.5}$ contributed 88.5% of the total Chinese DALYs attributable to IAPs. Although DALYs attributable to $PM_{2.5}$ decreased by 18.4% between 2000 and 2017, $PM_{2.5}$ continued to rank the highest. This means that controlling indoor $PM_{2.5}$ exposure remains a major priority for China. As expected, the rankings for specific IAPs according to attributable DALYs differ among provinces in China. For example, the top five IAPs in more than ten provinces include ozone, formaldehyde, and sulphur dioxide. Therefore, different provinces have different priorities for indoor air pollution problems to address.

How do these findings compare with other studies and, in particular, with assessment in developed countries? To answer this question, the study compared DALYs attributable with IAPs in China with those in the USA and European countries (Fig. 1b). The DALYs attributable to IAPs in China were 1.84 times those of the USA in 2010, and 3.85 to 6.01 times those of European countries in 2004. There were also disparities in pollutant rankings between China and other countries, due to differences in the condition of building stock, how buildings are used, outdoor pollution and meteorology. For instance, the IAP burden of benzene was notably higher in China than in European countries. Additionally, between 2004 and 2010, the disease burden ranking associated with indoor carbon monoxide increased significantly as a result of China's specific circumstances. The BOD attributable to IAPs was 9.50% higher than those of outdoor air pollution in China in 2017, which further demonstrates the role of indoor air pollution and that the problem will not disappear even in the absence of outdoor air pollution.

Interestingly, while the ranking of pollutants varies between provinces and between China, the US and European countries, the main pollutant, $PM_{2.5}$, is the same for all the countries, and its impact in terms of BOD exceeds by far the impacts of all other pollutants. Overall, this demonstrated that there are major factors that are generalisable across countries, regardless of the level of development.

The WHO AQGs, published in 2021 [16], are health-based numerical air quality guidelines. I had the privilege of co-chairing this process, the beginning of which motivated the team to conduct the study in China. While the exposure–response curves were established based on outdoor data, as no relevant studies were conducted indoors, the document emphasises that the guidelines apply to both indoor and outdoor air.

Therefore, with the availability of AQGs, the CBD–IAP study provided two key prerequisites for establishing national IAQ standards: quantification of the BOD due to IAP (and demonstrating that it ranks third among all risk factors in China) and the establishment of its economic cost. The importance of this cannot be overstated. The establishment of outdoor air quality standards and legislation resulted in significant improvements in air quality in China; similar public health benefits are expected to be achieved by establishing IAQ standards.

The WHO AQGs apply to indoor and outdoor air; however, this does not mean that national outdoor air quality standards automatically become indoor air quality standards. Enforcement of the standards will require routine indoor air compliance monitoring in all public spaces. The very different realities of indoor and outdoor environments mean that we cannot automatically use outdoor air quality standards as indoor standards. Pragmatically, we can only monitor a small number of pollutants indoors. CBD–IAP's discovery of the role of $PM_{2.5}$ and the universality of this role around the world made it a leading contender for IAQ standards.

While it was difficult to raise awareness about the importance of indoor air quality and the need for IAQ standards before 2020, the COVID-19 pandemic brought this issue into full focus. From the angle of infection transmission, the aim was to reduce the concentration of pathogens in the air and therefore the risk of infec-

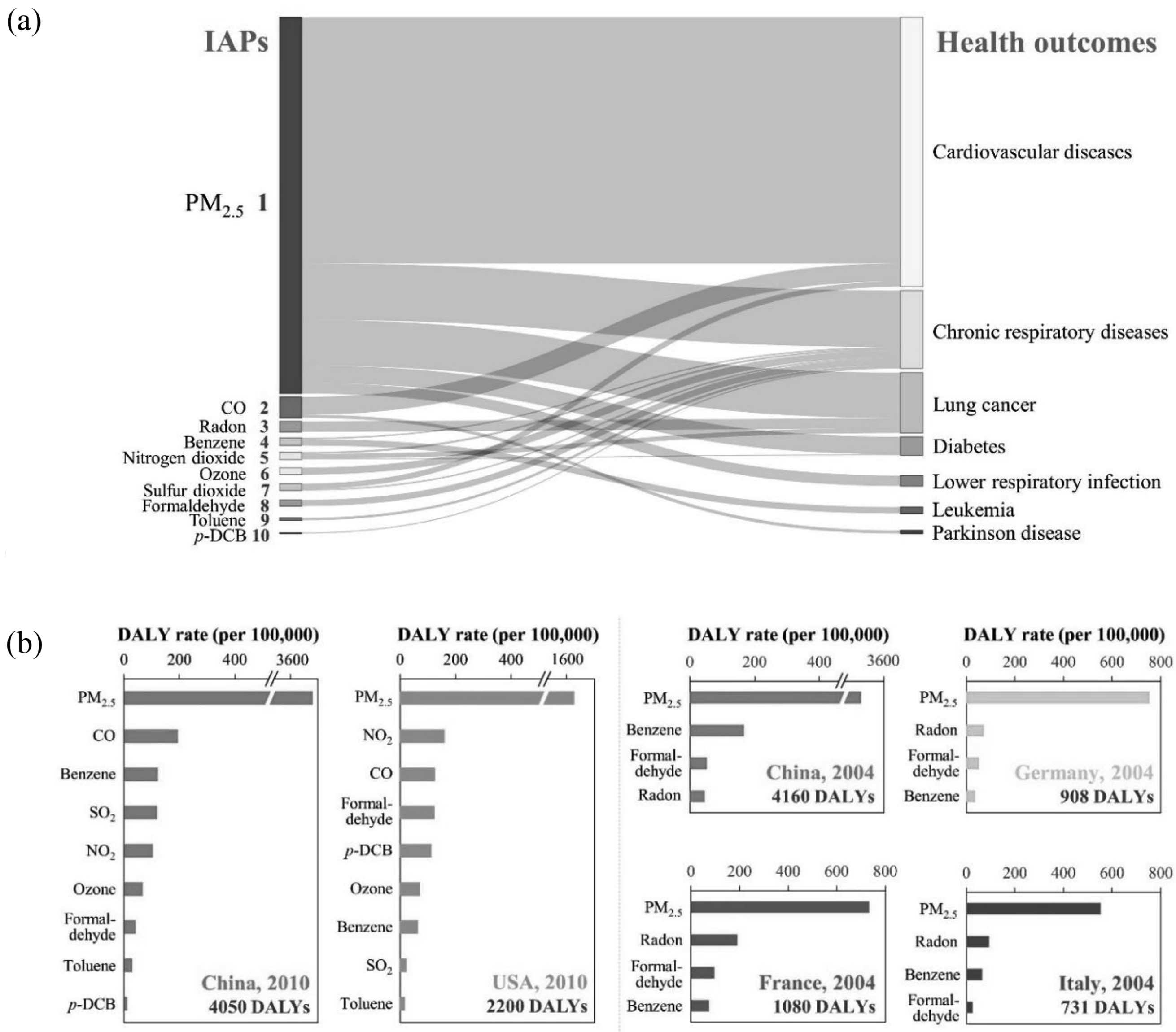

Fig. 1. (Color online) (a) DALY rate of indoor air pollutants in China in 2017; (b) comparison of DALY rate (per 100,000) for different countries.

tion; in this context, the role of building engineering, in particular ventilation, was highlighted [17]. This was not a new concept [18,19], and during the pandemic numerous studies demonstrated the role of ventilation in reducing COVID-19 infection rates (e.g., Buonanno et al. [20]). Recently, Morawska et al. [21] provided a "blueprint" of IAQ standards to combat infection transmission with two parameters included: CO_2 (as a proxy for infection risk) and ventilation rate, along with their numerical values. Allen et al. [22] provided additional evidence for a higher value for the ventilation rate.

With this backdrop, the CBD–IAP study brings us one step closer to our common goal: making clean indoor air the norm by providing key evidence necessary for controlling indoor pollution risks, and a broader foundation for IAQ standards. The authors of the paper [9] are to be congratulated for this work and their important contribution to a dream that the safety of indoor air will be ensured by routine monitoring that will provide data for every public indoor environment so that we can take each breath of indoor air as safely as we can already take a sip of tap water (in most countries around the world). Future directions of this work should expand these analyses to include the BOD due to indoor airborne infection transmission. Although the COVID-19 pandemic was outside the period of this study, airborne transmission of many respiratory infections, including seasonal influenza, RSV or the common cold, is a common occurrence and a major public health problem, as well as an economic burden. Another extension of this work should be to include analysis of the BOD due to exposure in shared public spaces, such as schools, offices, and entertainment venues. People spend a significant fraction of their lives in such places and therefore it is important to understand the impact of IAQ on public health in order to control it.

Conflict of interest

The author declares that she has no conflict of interest.

Acknowledgments

This work was supported by the Australia Research Council (ARC) Industrial Transformation Training Centres (ITTC) "ARC

Training Centre for Advanced Building Systems Against Airborne Infection Transmission" (IC220100012) and ARC Laureate Fellowship (FL220100082).

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