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Cardiovascular Effects of Indoor Air Pollution from Solid Fuel: Relevance to Sub-Saharan Africa

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Abstract

Purpose of Review This research aims to summarize evidence on the cardiovascular effects of indoor air pollution (IAP) from solid fuel and identify areas for research and policy for low- and middle-income countries.

Recent Findings IAP affects people from low socioeconomic status in Latin America, Asia, and Africa, who depend upon biomass as a fuel for cooking, heating, and lighting. In these settings, IAP disproportionately affects women, children, the elderly, and people with cardiopulmonary disease. The health effects of IAP include acute respiratory infections, chronic obstructive pulmonary disease, pneumoconiosis, cataract and blindness, pulmonary tuberculosis, adverse effects to pregnancy, cancer, and cardiovascular and cerebrovascular disease. New methods for assessing individual IAP exposure, exposing pathways of IAP-related cardiovascular disease, and performing qualitative research focusing on population preferences regarding strategies to reduce IAP exposure have been the most important developments in tackling the burden of IAP. Unfortunately, major disparities exist regarding research into the cardiovascular effects of IAP, with only few studies coming from sub-Saharan Africa, despite this region having the highest proportion of households using solid fuels.

Summary Premature cardiovascular deaths and disability can be averted in low-middle income countries by addressing biomass fuel usage by the most disadvantaged settings. While research is needed to uncover the mechanisms involved in cardiovascular outcomes linked to IAP, immediate action is needed to educate the most affected populations on IAP health hazards and to reduce their exposure to this environmental risk through promoting improved housing and better ventilation, as well as increasing access to affordable clean cooking energy.

Keywords Indoor air pollution · Biomass fuel · Cardiovascular diseases

Introduction

Indoor air pollution (IAP) from solid fuel—or household air pollution—is the single most important environmental risk factor for disease worldwide [1, 2], and one of the top 10 causes of death worldwide [3], representing an important and major driver of health services demand [4]. A preventable cause of premature death, IAP is a poverty-related global health problem responsible for more than 7 million deaths annually [5], predominantly in lower socioeconomic

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segments of the population [6, 7]. Indeed, IAP disproportionately affects people of low socioeconomic status in low- and middle-income countries (LMIC) of Asia, Latin America, and Sub-Saharan Africa (SSA), mainly related to use of biomass fuel for cooking, lighting, or heating purposes [8, 9].

Nearly half the world's population burns solid and biomass fuel [8–10], generating volatile gases and respirable particulate matter (PM) that are associated with acute and chronic disease [11, 12], as well as with increased risk of death (https://sustainabledevelopment.un.org/content/documents/1008357_Piqueras_The rapidly growing death toll attributed to air pollution-A global responsibility.pdf) [5, 13]. High-risk groups include children, women, the elderly. and people with underlying chronic conditions [9, 14, 15•]. Women and children experience higher IAP exposure due to women's traditional roles in performing indoor work, cooking, and childcare [14, 15•, 16].

Regional and national variations in exposure to biomass fuels determine a burden of disease that varies in different parts of the world. Biomass fuels (wood, charcoal, dung, and agricultural residues) are vital to basic welfare and economic activity in developing nations, especially in SSA, where they meet more than 90% of household energy needs in many nations. It is estimated that in 2000, households in SSA consumed nearly 470 million tons of wood fuels (0.72 tons per capita) in the form of wood and charcoal [17]. In Africa, charcoal is widely used, even in countries with large endowments of fossil fuels, such as Gabon, Angola, and Nigeria [18]. Around 700 million people in this region rely on biomass fuels for cooking and heating, and it is estimated that IAP contributes to as many as 600,000 deaths, making it the region with the highest deaths per capita related to this risk factor (https://sustainabledevelopment.un.org/content/documents/1008357_Piqueras_The rapidly growing death toll attributed to air pollution-A global responsibility.pdf).

Several adverse health effects have been associated to long exposure to smoke from indoor biomass burning. This narrative review of literature summarizes evidence on the effects of components of IAP in the cardiovascular system. We focus on cardiovascular disease in SSA due to its unique profile and the high exposure to IAP in this region, and aim to explore new knowledge to support interventions to prevent premature deaths determined by IAP in the most affected areas of the world. Given the different methods used to assess the association between cardiovascular disease and IAP, positive and negative results are described to provide an overall trend emerging from the literature. We also describe approaches used in IAP exposure assessment, interventions used to reduce its health consequences, and the challenges to apply them globally. In LMIC, unplanned growth of human settlements near industrial plants and industrial processes such as mining, fuel refinery, chemical manufacturing, livestock waste, commercial cooking, and wildfires contribute to high pollution levels in surrounding houses and their environs. Additional sources of IAP include secondhand tobacco smoke, use of incense, household products, pesticides, and building materials (e.g., asbestos), but these are not explored in this review.

Scope of the Problem

Exposure to IAP may be responsible for nearly 2 million excess deaths in developing countries and for some 4% of the global burden of disease [19]. Biomass represents 10% of the world's primary energy use, with almost 2.7 billion people worldwide using biomass fuels for their household energy needs. It is estimated that by 2030, 2.8 billion people will be using biomass fuel [20]. However, the percentage of the population relying on household use of solid fuels for cooking varies significantly among countries (urban and rural areas) and regions. Africa and South-East Asia have the highest proportion of households using solid fuels, with 77% and 61%, respectively [8].

Despite an overall reduction in the number of pollution-related deaths since 1990, falling from 3.7 to 2.6 million in 2016, deaths from air pollution are largely concentrated in Asia and Africa: three quarters of all deaths in 2016 were in Asia, with 22–23% in Africa and the Middle East [21]. Nigeria, Ethiopia, and Democratic Republic of Congo are the countries with the highest number of deaths due to IAP in SSA in 2016, with, respectively, 64,486; 62,153; and 52,788 deaths.

Deprived communities from rural SSA, Asia, and Latin America rely heavily on biomass fuel for cooking or heating purposes [22]. In these regions, reliable and affordable access to clean fuels (liquid petroleum gas, biogas, and electricity) is limited to a relatively small portion of the population, usually living in urban centers [22]. Wood is the most common biomass fuel, but charcoal and crop residue are also used. In rural areas with limited vegetation, animal dung (such as cow, sheep, and horse) is equally used, due to its lower cost [23]; this particularly occurs among pastoralist communities living at high altitude (e.g., Nepal, Afghanistan) or in savannahs where wood is rare (e.g., Kenya, Ethiopia). Animal dung is the least efficient biofuel, burns faster as compared to wood [24], and its combustion produces 23% more PM with a small aerodynamic diameter per kilogram, toxic byproducts, and oxidizing species as compared to wood smoke [25, 26].

Certain cultural practices and habits of communities in these regions increase exposure and thus the health risk associated with IAP. The observed age and gender-dependent gradient in exposure to IAP in rural SSA reflects differences in household cooking activity and time spent indoors [15]. Indoor cooking in poorly ventilated houses exposes women and children to $PM_{2.5}$ at levels that are 1000 times higher than the WHO recommended threshold (25 $\mu g/m^3$) [27, 28].

Determinants of IAP

In LMIC, exposure to IAP occurs both in rural and urban populations, and may be difficult to measure since living habits and practices in rural communities make it difficult to clearly separate indoor from outdoor air pollution. On the other hand, people spend considerable amount of time outside the house in daily activities and, there may be crossed exposure from air pollutants from neighboring houses. Finally, households may vary their use of solid fuel and electricity or gas, according to their (often fluctuating) financial situation.

The level of exposure to IAP may be determined by positioning of the stove, kitchen characteristics, and stove types. People in different parts of the world use different cooking and heating appliances, and have different types of housing, ventilation (such as the presence of a chimney that vents to the outside of the house), and characteristics of the kitchen (building material, architectural features that influence indoor air quality, location of the kitchen with relation to living area, etc.).

Poverty and low socioeconomic status—measured by income, education, occupation, housing type, water and electricity access, as well as assets [29, 30]—are key determinants of IAP exposure. Communities with low access to clean fuels, high unemployment rates, high percentage of the population living in extreme poverty, and high income inequality Gini coefficient [31–33] tend to be exposed to higher levels of IAP. Overall, 82% of households rely on solid fuels for cooking in SSA (95% rural versus 66% urban); the fuel types are distributed as follows: wood 69%, charcoal 11%, coal 1%, and dung 1% [8, 34]. Countries such as Mozambique and Malawi, among the poorest worldwide, have higher usage of biomass fuel for daily living activities [8, 34, 35]. In Mozambique, approximately 95% of households burn solid fuels for cooking [8], with wood being typically used in rural settings and charcoal in urban areas [34]. Similarly, in Malawi, charcoal is used in 81.5% of households and wood in 36.5%; only 3.9% use exclusively electricity and a lower educational and occupational attainment was associated with greater use of wood [35].

In Latin America, the statistics suggest a proportionally smaller contribution of residential heating [36], but data are based on nationally aggregated statistics of energy consumption, which do not take proper account of residential heating and cooking. Although development indicators have generally improved in this region over the last decades [37], socioeconomic gradients among countries and inequities within countries are evident and persistent; rural populations are still exposed to outdoor air pollution from open burning associated with agricultural practices [38–40] and wood burning used in residential heating and cooking [41, 42].

Low-socioeconomic-status communities face higher exposure to IAP and have increased susceptibility to poor health; this contributes to health disparities driven by environmental factors [43–45]. However, larger efforts are needed to characterize inequality in less-industrialized nations, where routine ambient air quality monitoring is lacking [46••]. One solution to overcome this lack of routine air quality monitoring is the use of extensive mobile monitoring coupled with the placement of several fixed site monitors, as well as census of wood and charcoal stoves along the mobile monitoring route [44, 45]; this combination allows the creation of exposure maps that reveal significant spatial variability both within and between neighborhoods [47, 48]. In-country disparities were exposed in South Africa, where despite 92% of households having electricity, in families described as being the most deprived, fossil fuels were still used for cooking (19%) and heating (15%) [49]. A summary of data on population access to clean fuels, unemployment rates, percentage of people with extreme poverty, inequality index, and deaths attributed to IAP in countries within Southern Africa is presented (Table 1).

Combustion of biomass fuel using inefficient stoves generates the following: (i) toxic gases like carbon monoxide and nitrogen oxides; (ii) suspended PM containing volatile organic compounds such as methane, aldehydes, benzene, and its derivatives; and, (iii) polycyclic aromatic hydrocarbons like benzo[a]pyrene and anthracene [50]. IAP from biomass fuel consists of a mixture of solid particles, liquid droplets, or gases in the air that can adversely affect human health and the surrounding ecosystem. The quantity and type of biomass fuel used influence the pollutants released to the air; different biomass fuels are associated with different levels of particulate pollution.

Finally, there seems to be individual susceptibility to the effects of IAP in humans. Lung cancer has been associated with smoke from domestic fuel [51–53] but there seems to be a variation in the risk associated with different fuel types [52–54]; these observations from Hosgood et al also provided evidence for individual susceptibility linked to genetic variation in determining association between IAP and lung cancer risk in non-smoking populations. On the other hand, being overweight or obese has been shown to increase susceptibility to indoor PM2.5 and NO_2 in urban children with asthma [55]. Whether this is also true for cardiovascular risk and disease related to IAP is something that needs to be determined.

Adverse Cardiovascular Effects

The different biomass fuels are associated with different levels of particulate pollution and theoretically may have diverse health effects [56]. The effects that have been more explored include acute respiratory infections on children, chronic obstructive pulmonary disease, pneumoconiosis, cataract and blindness, pulmonary tuberculosis, and adverse effects to pregnancy, cancer [12, 14, 57, 58]. However, air pollution is

Table 1 Sociodemographic data, inequality index, access to clean fuels and IAP-related deaths for countries in Southern Africa showing

Country	Population (2018)	Access to clean fuels (%) (2014)	Unemployment rate (%) (2017)	People in extreme poverty (%) (2008)	Income Gini coefficient (2013)	Deaths attributed to IAP (2016)
Angola	30,774,205	47.9	20.0	54.3	42.7	7902
Botswana	2,333,201	62.5	18.1	–	60.0 (2009)	450
Lesotho	2,263,010	6.0	27.2	57.8	52.5	1486
Madagascar	26,262,810	2.0	1.8	67.3	44.1	21,146
Malawi	19,164,728	3.2	5.9	72.9	43.9	11,311
Mozambique	30,128,673	44.0	25.0	74.7	45.7	17,154
Namíbia	2,587,801	45.9	29.9	–	63.9	802
South Africa	57,398,421	81.8	26.7	26.2	63.1	6934
Swaziland	1,391,385	49.7	26.4	62.9	51.5	455
Tanzania	59,091,392	2.0	2.2	88.5	37.6	33,024
Zambia	17,609,178	16.1	7.8	64.3	57.5	10,675
Zimbabwe	16,913,261	31.3	6.6	–	43.0 (2011)	7676

Worldometers (http://www.worldometers.info/world-population/southern-africa-population/)

an independent risk factor for cardiovascular morbidity and mortality [12, 14, 58], and has been shown to affect health service demand of the patients with cardiovascular and cerebrovascular diseases [4]. An increase of 10 $\mu g/m^3$ of PM2.5 produces 4%–6% rise in overall mortality, 10% increase of cardiovascular disease prevalence, and also increases acute hospitalizations, particularly among susceptible populations [59]. It has been shown that environmental pollutants can cause induction and progression of certain cardiovascular conditions [60••, 61] and may lead to enhanced coagulation, thrombosis, arrhythmias, atherosclerosis, hypertension, and coronary artery disease [62].

Despite a growing body of research linking IAP with subclinical indicators of cardiovascular disease risk including blood pressure, carotid atherosclerotic plaque, and arterial stiffness, direct evidence of this role remains highly needed. Since IAP has been understudied with respect to cardiovascular disease [63], most of our pathogenic hypothesis arose from ambient air studies and more specific research is needed. Although the impact of IAP on health indicators in the SSA region is probably underestimated, population-related vulnerabilities and individual-level susceptibilities may influence exposure-response relationships of IAP in the region. Among vulnerabilities relevant to SSA poverty, multiple overlapping socioeconomic risk factors, access to quality health care, and co-prevalence of chronic and infectious diseases (e.g., tuberculosis, schistosomiasis, and HIV) may be the most important.

Overall, there are plausible pathways to cardiovascular disease via high-level exposure to IAP and given the socioeconomic and environmental circumstances of SSA, IAP may well be pivotal in producing a burden of disease that is markedly different from high-income countries. This is particularly relevant to the observed high occurrence of right heart disease in particular in younger individuals and women in SSA [64]. There is, however, scarcity of data on the associations between IAP and prevalent cardiovascular risk factors and diseases in SSA, which is in itself a sign of global health disparity. In the next paragraphs, we summarize the findings from studies performed in Africa trying to explore the link between IAP and cardiovascular outcomes, which are published on PubMed.

For hypertension, the leading cause of acute heart failure in SSA [65], studies examining its link to air pollution worldwide gave controversial results. Ofori and colleagues [66] revealed significant association between biomass fuel use and increased systolic blood pressure, carotid internal media thickening, and pre-hypertension in a cross-sectional study of 389 adult women from Nigeria.

Rheumatic heart disease (RHD), a complication of Group A streptococcal infection that has been almost eliminated in developed countries, is probably the most preventable of all cardiovascular diseases, but is still very prevalent in SSA [67]. Despite being considered a poverty-related disease, the role of specific social and environmental factors in streptococcal infection and progression to RHD are not well understood. Recently, evidence of an association between air pollution in early life and the development of valvular rheumatic heart disease was published [68]. Estimates of air pollution and social conditions that had been developed in 1951–1952 for 83 UK urban areas were related to subsequent RHD mortality rates at ages 35–74 in men and women from 1993 to 2012. In multiple regression analyses, a strong correlation between domestic air pollution and RHD was found (relative risk per SD increase in pollution 1168, 95% CI = 1128 to 1210, $p < 0.001$), independent of social class, education, crowding and population density [68]. While recognizing that the study relied upon data derived from a number of sources and collected in different time points, and that there were no direct measurements of smoke exposure, there is biological plausibility that suggests a causal link.

Right heart failure (RHF) and pulmonary arterial hypertension (PAH) were common among Africans presenting with de novo heart disease in South Africa. Of the 2505 case patients with heart failure, 697 (28%) had RHF (50% had RHF as their primary diagnosis) [64]. Among the pathways to RHF, chronic lung disease (179 cases, 26% including chronic obstructive pulmonary disease and tuberculosis) and PAH (141 cases, 20%) were the most frequent causes, after concurrent left-sided heart disease (213 cases, 31%). Interestingly, women were almost two times more likely to present with PAH (OR 1.72, 95% CI 1.17–2.55; $p = 0.006$), suggesting gender-related risk factors that may include IAP [65]. More recently, IAP was identified as a risk factor in women with isolated RHF in Kenya [69•]. One study looking specifically into IAP in Egypt evaluated 355 families using questionnaire and direct observation, as well as measurements of samples of water collected indoor and outdoor, did not show any association between IAP and cardiovascular disease [70]. The studies that explored indoor air pollution as a risk factor for cardiovascular outcomes in SSA, and published in the last 5 years are summarized in Table 2 [66, 68, 69•].

Evidence-Based Interventions to Reduce the Impact of Biomass Fuels

Interventions to reduce exposure to IAP from biomass fuels include advanced charcoal stoves, bioethanol clean stoves, liquefied petroleum gas stoves, increased housing ventilation, and reduction of cook smoke time. Over time, there have been global efforts to reduce IAP from biomass use and associated health effects in LMICs [71–73]. Until recently, these efforts focused on developing and distributing cook stoves that improve fuel combustion efficiency [71, 72]. However, improved cook stoves (ICS) have had poor uptake and failed to demonstrate reduction in IAP levels or health effects [74, 75], leading to a shift in focus to cleaner fuel alternatives, particularly liquid propane gas, biogas, and electricity [76, 77].

The type of fuel being important [78], bioethanol was tested and showed significant reduction of TNF-α levels in pregnant women, suggesting a lower risk of cardiovascular stress and pro-thrombotic events associated with its use [79]. Women receiving bioethanol ICS showed a trend to lower post-intervention systolic blood pressure on ambulatory monitoring [79].

Anenberg and colleagues estimated the potential air pollution-related health benefits of four illustrative scenarios, in which traditional cooking fires and stoves would be replaced by cleaner and more efficient technology in Mozambique [80]. For rural areas, a 10% increase in the number of households using ICS would achieve > 2.5 times more health benefits from reduced PM2.5 exposure (200 premature deaths avoided and 14,000 disability adjusted life years (DALYs), avoided over a 3-year project lifetime) compared to natural draft stoves in the same households, assuming 70% of households using the new technology. Expanding LPG stoves to 10% of households in five major cities in the country would potentially avoid 160 premature deaths and 11,000 DALYs from reduced PM2.5 exposure over 3-year intervention, assuming that 60% of households would use the new stoves. Advanced charcoal stoves would achieve approximately 80% of the PM2.5-related health benefits of LPG stoves, resulting in 2–5% additional health benefits [80].

Change of housing design and improvement of air ventilation are alternative ways to improve household's environment, since poor rural households often lack the resources to obtain cleaner, more efficient fuels and appliances. People should be encouraged to construct fireplaces whereby smoke is diverted to the outside, to avoid getting smoke into the living rooms, and to improve house design to have bigger windows to promote better ventilation.

The results of a systematic review to determine if IAP interventions were associated with improved indoor air quality in households in LMICs called for caution in concluding that the currently designed and implemented IAP interventions support reductions in the average kitchen and personal levels of PM and CO in these settings; moreover, the evidence that current stand-alone HAP interventions yield any health benefits is limited and post-intervention levels of pollutants were generally still higher than those recommended by WHO guidelines [81].

Challenges for Using Evidence-Based Interventions

There can be no argument regarding the direct and indirect evidence of the role of IAP in determining cardiovascular disease in LMIC. A considerable proportion of the population in Asia and Africa use biomass fuel and is exposed to it from birth; this population is expected to suffer greatly if nothing is done. However, compared to countries in Asia, African countries do not prioritize research into IAP and have not been able to apply evidence-based interventions for exposure reduction. This is partially due to a lack of human and material resources, but also to the perceived low health risk associated with IAP in rural and underserved areas, and may explain why research on biomass fuel has been neglected, when compared to a

Table 2 Original research on cardiovascular effects of indoor air pollution from SSA published on PUBMED in the last 5 years

Author Year Country	Aims Study Design Population	Cardiovascular outcomes	Key findings and conclusions
Ofori et al. 2018 Nigeria [66]	Explore the association between biomass fuel (BMF) use and blood pressure (BP) and carotid intima media thickness (CIMT) Community-based cross-sectional study of 389 rural dwelling women aged 18 years and older	BP CIMT	1. Statistically significant difference in the mean systolic BP and CIMT among BMF users compared to non-BMF users 2. The use of BMF was significantly associated with 2.7 mmHg higher systolic BP and increased odds of pre-hypertension (OR 1.67 95% CI 1.56, 4.99, $p = 0.035$) but not hypertension (OR 1.23 95% CI 0.73, 2.07, $p = 0.440$)
Phillips et al. 2017 Uganda [68]	Explore association between air pollution in early life and subsequent death by rheumatic heart disease (RHD) Retrospective study of 3939 deaths from chronic RHD occurred from 1993 to 2012 in people aged 35 to 74 (2609 women) in 78 urban areas in England and Wales, relating them to IAP estimates and social conditions (by Daly, 1951–52)	RHD mortality rate	Evidence of an association between air pollution in early life and RHD 1. Strong relationships between domestic air pollution and RHD (RR per SD increase in pollution 1.168, 95% CI = 1.128 to 1.210, $p < 0.001$) 2. Strongest relationships were between RHD mortality and domestic pollution and overcrowding
Lagat et al. 2014 Kenya [69•]	Explore environmental exposures and comorbidities associated with isolated right heart failure (IRHF) in women Community-based case-control study (31 cases and 65 controls)	Isolated right heart failure	1. Surrogate measures of indoor air pollution were not associated with IRHF 2. Lower kitchen ventilation, airflow limitation, HIV, and occupational dust exposure were associated with IRHF

CI confidence interval, *OR* odds ratio, *RR* relative risk, *SD* standard deviation

predominant focus on infectious diseases and other risk factors for chronic diseases.

While ICS have been considered a global priority, promoting its exclusive and sustainable use is very challenging. Cost and lagging infrastructure are recognized barriers, but knowledge gaps and acceptance of these technologies at the community level must be addressed to optimize adoption and use, since they may be influenced by perception of cultural appropriateness, household preferences, provision of incentives, and socioeconomic factors [82, 83]. For example, a community survey in rural Senegal found that biomass fuel use was ubiquitous, with less than 1% of households that owned an LPG using it as the primary cooking device, and that multiple traditional stoves were used, even when cleaner burning alternatives were available [83]. Despite 92% of households using traditional open fire, women preferred propane gas and ICS. However, while they appreciated that ICS reduced smoke exposure, they thought that currently available options (including LPG) did not address all of their preferences. The stove features of greatest value to them were, in order: large cooking capacity, minimal smoke production, and rapid heating. Despite the low desirability and smoke emissions from the traditional open fire, its use in the presence of alternative stove options may be related to its ability to satisfy some of the practical needs of the women, namely large cooking capacity as well as rapid and intense heat generation [83].

Future Research Directions

The 2030 Agenda for *Sustainable Development*, adopted by all United Nations Member States in 2015 [84] places greater emphasis on reducing the health impacts from ambient air pollution in developing countries. Future research should aim to (i) standardize effective methods to measure personal exposure to IAP; (ii) design and implement studies to determine the specific mechanisms underlying IAP-related cardiovascular disease; (iii) test pragmatic and culturally accepted interventions to reduce IAP and perform qualitative research to support its adoption; and (iv) quantify the region-specific and overall burden of IAP-related cardiovascular disease to better inform the cost-benefits of promising prevention strategies. Additionally, there is a need to assess and better understand how the different types of fuels compare to each other.

1. Standardizing effective methods to measure personal exposure to IAP

   Data on personal exposure to IAP is lacking and, where available, it is generally collected using non-comparable, study-specific, and indirect methods of exposure assessment. These include comparing household fuel use or housing type as proxies for personal exposure [85], as well as fixed monitoring within homes to estimate personal exposures to IAP constituents [86–89]. Few studies have measured personal exposure to IAP worldwide, and even less in SSA [15, 90, 91].

Spatial and temporal variability of urban air pollution levels combined with indoor exposures and individual's time-activity patterns are key elements of personal exposure assessment. Analyzing individual exposure offers several challenges in both urban and rural areas where the individual's activities as well as outdoor air pollution levels demonstrate a large degree of spatial and temporal dynamics. New conceptual structures to organize personal exposure assessment methods have been proposed to address spatial-temporal variations of individuals' activities (point-fixed or trajectory based) and variability of air quality in urban settings [92••]. Use of trajectory and variable air quality provides a promising framework for tackling inter- and intra-variability of individual exposure, but quantitative comparison between the different approaches should be performed taking into account the purpose of the health study [92••].

2. Understanding the mechanisms involved in cardiovascular damage by IAP

   It is now well accepted that traditional cardiovascular risk factors (such as high blood pressure and diabetes) alone cannot explain the huge burden and differential pattern of cardiovascular disease in LMIC [93]. IAP may be the non-traditional risk factor that independently accounts for most unexplained cardiovascular events and disability worldwide (particularly in women and younger individuals), and thus should be measured in community-based surveys for NCD risk factors and chronic diseases in LMIC.

3. Testing of interventions to reduce IAP and qualitative research

   Promoting models of housing with better ventilation, achieving wide access to clean household fuels, and ensuring its sustained adoption at scale, are important ways for obtaining reductions in IAP to levels that are sufficient to impact on the substantial global health burden determined by reliance on solid fuels. Enablers and limiting factors at household, community, and national levels need to be addressed. These include understanding the collateral effects of usage of different types of fuel by the communities, exploring how the population accepts these new technologies, addressing household and setting characteristics that increase accumulation of pollutants, as well as assessing people's knowledge and perceptions regarding the proposed alternatives. At the population level, there might be need to (i) introduce taxes and/or subsidies; (ii) work on market development and regulation; (iii) develop legislation and establish standards; and; (iv) introduce policy mechanisms to eventually sustain these gains.

   Qualitative research is also recommended to address acceptability of potential solutions. Ease of use, time efficiency, fuel efficiency, and perceived smoke reduction of ICS, were considered very important in Kenya [94]. User's perspectives and acceptability should inform research and development of technologies that are both effective in reducing IAP and practical in use. Finally, countries with large gas reserves should be encouraged (based on a wise investment in public resources to protect future population health) to progressively increase usage of liquid gas and create mechanisms of purchase flexibility for the diverse household user base [95]. Co-funding by the government or developed by the private sector is potentially a facilitator; it should target specifically underserved communities in remote areas [96] and provide support for low-income household customers with intermittent cash who cannot purchase standard-sized cylinders [94].

   In Bangladesh, an analysis of consumer needs and preferences assessed household ICS trials, fuel, and stove use monitoring, and consumers' perceived value of and willingness to pay for ICS [97]. Although these cook stoves were appreciated and liked, no models met consumer needs sufficiently to replace traditional stoves. While many users preferred ICS over traditional stoves, this preference decreased over the 3-week trial period. Complaints and suggestions for improvement carried from fairly simple modifications to the stove design, to more complex including the need for point-of-purchase consumer education and follow-up from service agents or health outreach workers. Fuel use reductions were lower than expected, partly because of continued parallel traditional stove use, but there was indication that users valued the ICS when acquisition barriers were removed, highlighting the need for better financing options [97].

   Interestingly, solutions can also be born in the African continent, such as the case of a company built by an entrepreneur across Rwanda (called *Inyenyeri*) aiming to replace Africa's overwhelming dependence on charcoal and firewood with clean-burning stoves powered by wood pellets (https://www.nytimes.com/2018/12/06/business/rwanda-charcoal-pellet-stoves-.html). *Inyenyeri* presents a real-world solution that attracts those focused on economic development, who propose that profit-making businesses may be best positioned to deliver critically needed services to the world's poorest communities (https://www.nytimes.com/2018/12/06/business/rwanda-charcoal-pellet-stoves-.html).

4. Defining the cardiovascular burden of IAP

   Longitudinal community-based studies aimed at showing the presence of IAP in areas with high prevalence of cardiovascular disease are needed. Studies to assess different risk factors together and in isolation are also important. Dual exposure to smoking and IAP has been shown to be associated with increased asthma in adults [98], suggesting that the role of smoking, secondhand tobacco, and incenses in exacerbating or accelerating the incidence of cardiovascular outcomes should also be explored.

Importantly, screening for cardiovascular disease potentially related to IAP may create evidence to support interventions in the communities and allow the measurement of their impact in reducing adverse outcomes. Finally, high-quality data on household energy practices, patterns of IAP. and related cardiovascular conditions is needed for efficient policy making, particularly in SSA.

Conclusions

Few studies on cardiovascular effects of IAP pollution have been conducted in SSA, where the highest measured exposure levels are recorded worldwide, contributing to global health disparity. High-quality data on energy practices, patterns of exposure, and IAP-related disease profile are needed for efficient policy making in the most affected regions, particularly in SSA. However, while research is needed to uncover the mechanisms involved in cardiovascular outcomes linked to IAP, immediate action is needed to educate the most affected populations on IAP health hazards and to reduce their exposure to this environmental risk through promoting improved housing and better ventilation, as well as increasing access to affordable clean cooking energy. Importantly, effort should be made to explore the best strategies to monitor the impact of these interventions at an individual, regional, and global level.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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•• Of major importance

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