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REVIEW ARTICLE

Everyone has heard, and t-shirts can be bought emblazoned with, the popular saying 'Home is where the heart is'. Lungs, too, it turns out. Hearts and homes convey images of peace and security, protection and shelter. Lungs and homes, as we learn from this month's 2010: Year of the Lung feature article, have a different association. Homes of poor people are where lungs are likely to be injured from exposure to exceedingly high concentrations of toxins in smoke from biomass fuels and coal used in cooking and heating. Indoor air pollution, we are told, 'accounts for a substantial proportion of the global burden of disease in developing countries'. And that's not all: according to Doctors Perez-Padilla, Schilmann and Riojas-Rodriguez it is going to get worse before it gets better. Clean fuels are expensive. Efficient stoves can alleviate some of the emissions, but both cultural and behavioral barriers stand in the way of widespread acceptance. Much more needs to be done.

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Respiratory health effects of indoor air pollution

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SUMMARY

Domestic pollution is relevant to health because people spend most of their time indoors. One half of the world's population is exposed to high concentrations of solid fuel smoke (biomass and coal) that are produced by inefficient open fires, mainly in the rural areas of developing countries. Concentrations of particulate matter in kitchens increase to the range of milligrams per cubic meter during cooking. Solid fuel smoke possesses the majority of the toxins found in tobacco smoke and has also been associated with a variety of diseases, such as chronic obstructive pulmonary disease in women, acute respiratory infection in children and lung cancer in women (if exposed to coal smoke). Other tobacco smoke-associated diseases, such as tuberculosis, asthma, respiratory tract cancer and interstitial lung diseases, may also be associated with solid fuel smoke inhalation, but evidence is limited. As the desirable change to clean fuels is unlikely, efforts have been made to use efficient, vented wood or coal stoves, with varied success due to inconsistent acceptance by the community.

KEY WORDS: biomass smoke; coal smoke; indoor pollution; COPD; acute respiratory infection

BREATHING OF POLLUTED AIR is as old as mankind, particularly since the domestication of fire. Evidence of fire accompanied hominid remains from 500 000 years ago in China,[1] and offered people then a survival advantage through cooking foods, heating, and keeping bugs and beasts at a distance. When people built shelters for dwellings, they also brought pollutants into the indoor living space.[2]

Today, burning biomass—principally wood, crop residues, and dung—remains an important source of exposure to a variety of toxins, mainly in the rural areas of developing countries. Humans have cooked in a similar manner for thousands of years. Fuels that

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are found at the top of the energy ladder, which are cleaner but also more expensive, have a much more recent history.

The exploitation of fossil fuels that are integral to modern living has been part of the rapid technological, social, and cultural changes of the past 250 years. Although such changes have brought about undeniable benefits, they have also contributed to the pollution of local and regional environments due to the release of a great number of chemicals.[3] People living in industrialized countries have other exposures due to more energy-efficient houses built from a variety of new building materials, plus chemicals and pets, in addition to a more sedentary lifestyle spent mainly indoors.

Total human exposure to air pollutants is determined by the concentrations found outdoors and indoors in the different microenvironments and the time spent in each of these environments, commonly called the time-activity pattern. People spend more than one half of their time indoors, with variations attributable to age, gender, and place. The National Human Activity Pattern Survey (NHAPS) showed that people in the United States and Canada spent an average of 87% of their time in enclosed buildings, and about 6% of their time in enclosed vehicles.[4] The average proportion of time spent indoors in rural areas of developing countries is, for women, 70% in Kenya and 75% in Mexico.[5,6] Although the fraction of time spent indoors is less in rural than in urban areas, individual exposures are often huge due to high concentrations of pollutants in indoor air. Therefore, indoor exposure, including that in occupational settings, dominates total exposure for many pollutants.

Indoor sources of air pollution can be categorized by type of source and by pollutant group, as shown in Table 1, which also depicts the main health effects

Table 1 Sources and characteristics of varied indoor air pollutants and associated health effects[7]

Pollutant*	Sources and characteristics	Associated health effects
Environmental tobacco smoke (ETS)[8]	A complex mixture of >4000 identified chemicals found in both vapor and particle phases. Many of these chemicals are known toxic or carcinogenic agents. Non-smoker exposure to ETS-related toxic and carcinogenic substances will occur in indoor spaces where there is smoking.	Secondhand smoke causes disease and even premature death in children and in adults who do not smoke. Children: sudden infant death syndrome (SIDS), acute respiratory infections (including bronchitis, bronchiolitis and pneumonia), tuberculosis, and more severe asthma, varied respiratory symptoms, delayed lung growth. Strong evidence of increased middle ear effusion, reduced lung function, and reduced lung growth. Adults: lung cancer in spouses of smokers, impaired breathing, aggravation of existing respiratory and cardiovascular disease, lowered defenses against infections, exacerbation of allergic responses.
Biological pollutants	Dust mites, molds, fungus, bacteria, products from men and pets, pests (cockroaches, mice, rats) enhanced by damp indoors. Also microbial products such as endotoxins, microbial fragments, peptidoglycans and varied allergens.	Major concern is allergic reactions, which range from rhinitis or conjunctivitis to severe asthma. Indoor allergens are important causes and triggers of asthma: dust mite, cats, cockroaches, dogs, and indoor molds and fungus. Also possible infections, hypersensitivity pneumonitis, and toxic reactions.
Volatile organic compounds (VOCs)	VOCs (toxic gases or vapors emitted at room temperature from certain solids or liquids) include formaldehyde, benzene, and perchloroethylene, among many others. The semi-VOCs category includes compounds such as phthalates. Sources include thousands of common products that are used daily, personal care products, household products such as finishes, rug and oven cleaners, paints and lacquers (and their thinners), paint strippers, pesticides, dry-cleaning fluids, building materials, and home furnishings.	Adverse effects are varied, including eye and upper and lower respiratory irritation. Formaldehyde has been classified as a probable human carcinogen by the Environmental Protection Agency (EPA), but can cause rhinitis, nasal congestion, rash, pruritus, headache, nausea, vomiting, dyspnea, and epistaxis. Symptoms after exposure to pesticides may include headache, dizziness, muscular weakness, and nausea. In addition, some active ingredients and inert components of pesticides are considered possible human carcinogens.
Radon	A naturally occurring underground radioactive gas resulting from the decay of radium, itself a decay product of uranium. Decay products, either free or attached to airborne particles, are inhaled.	Known human carcinogen. Radon is the estimated second leading cause of lung cancer, following smoking. While the risk to underground miners has long been known, the potential danger of residential radon pollution has been widely recognized only since the late 1970s, with the documentation of high indoor levels.
Asbestos	Asbestos may be found predominantly in insulation for heating systems, and mixed with cement, it is used in many countries for roofs and water deposits. When asbestos-containing material is damaged fibers may be dispersed into the air.	Known human carcinogen: lung cancer or mesothelioma, with synergic effects with tobacco smoking by approximately five-fold. Asbestosis requires important exposures that are more common in occupational settings.

*Combustion products are described in Table 2, which describes common pollutants in industrialized and developing countries except by occupational sources. Other possible toxins are lead from painted surfaces and free radicals.

associated with these pollutants.[2] Sources of pollution may result from combustion processes for cooking and heating; from human activities, such as smoking, presence of biological agents, and use of chemical substances; and from emissions of construction materials and furniture.[7] Indoor concentrations of pollutants depend on the quantity of emissions, the volume of the polluted space, and the rate of exchange between indoor and outdoor air. The principal indoor pollutants vary in rural and urban areas, and in developing and industrialized countries, but they are a source of disease everywhere. Industrialized countries employ several times more energy per person than developing countries, but because cleaner fuels are utilized, there is actually less exposure to pollutants than in developing countries.

This review will not deal with occupational exposure or environmental tobacco smoke;[8] it will center on the health effects of exposure to solid fuel smoke, mainly in developing countries. Recent reviews have dealt with domestic indoor pollution as a health problem in industrialized countries.[9,10]

INDOOR AIR POLLUTION IN DEVELOPING COUNTRIES

Household use of solid fuels is the most widespread source of indoor air pollution worldwide; solid fuels are extensively used for cooking and home heating in developing countries, especially in rural areas.[11–13] About 3 billion people in the world use solid fuels: 2.4 billion use biomass (wood, charcoal, animal dung, crop wastes), and the remainder utilize coal for the majority of their household energy needs.[14] The percentage of people using solid fuels varies widely among countries and regions, ranging from respectively 77%, 74%, and 74% in sub-Saharan Africa, South-East Asia, and the Western Pacific Region, to 36% in the Eastern Mediterranean Region, and 16% in Latin America and the Caribbean and in Central and Eastern Europe. In the majority of industrialized countries, solid fuel use falls below the <5% mark.[15]

The world map of solid fuel use can be superimposed nearly perfectly on that of socio-economic development. Moreover, use of solid fuels is invariably associated with poverty in countries, in communities within a country, and in households within a community. Health studies on indoor air pollution should always take into account socio-economic factors, which are powerful determinants of both disease and solid fuel use, and are difficult to control for in studies of solid fuel combustion products (Figure). For example, a study in Ghana concluded that poverty, lack of education, and a lack of awareness were the major factors affecting choice of cooking fuel, place of cooking, and level of respiratory health.[16]

In developing countries, especially in rural areas,

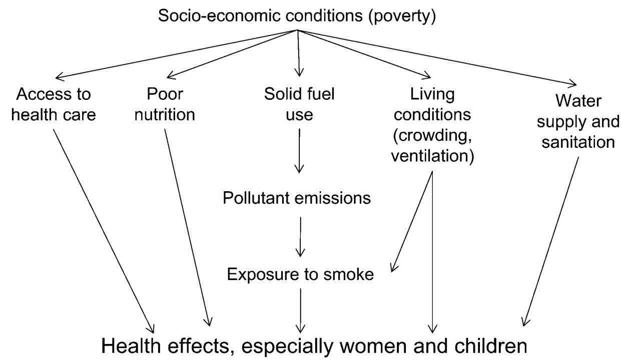

Figure Interactions between poverty, exposure to solid fuel smoke and ill health. One of the mechanisms linking poverty to disease is through the domestic inhalation of solid fuel smoke.

these fuels are often burned inefficiently in open fires, with high emission factors, leading to extremely high levels of indoor and local air pollution, many times higher than the limits specified by international standards of ambient air quality. Although open fires have energy efficiencies of only 5–10%, users perceive additional benefits, including space heating, protection from insects, and the flexibility of using a wide variety of fuels in different seasons.[17]

Levels of indoor particulate matter, which are commonly measured in milligrams per cubic meter, reach transient peaks of as high as 20–80 mg/m^3 when fires are started or stirred; these peaks form up to half of total exposure in women, as they are required to stay close to the fire while cooking. Particulate matter (PM) in biomass smoke has significant amounts of respirable size particles (mean aerodynamic diameter <10 μm, PM_{10}) and of particles <2.5 μm ($PM_{2.5}$), which are able to penetrate deeply into the lung. The concentration of particulate matter has been employed as an indicator of exposure to varying pollutants from biomass and other solid fuel indoor pollution. Other typical pollutants include carbon monoxide and a variety of toxins, carcinogens, and polycyclic aromatic hydrocarbons, which closely follow tobacco smoke toxins, except for nicotine.[11,18]

In view of the high concentrations of the many hazardous substances in smoke, exposure to indoor air pollution is particularly important for homemakers and young children, and accounts for a substantial proportion of the global burden of disease in developing countries.[3,14]

The use of biomass stoves is also a source of indoor pollution in industrialized countries, but stoves are usually vented and more efficient, producing concentrations of pollutants that are only a fraction of those typically found in developing countries. They are nevertheless above standard limits, have a negative impact on health and contribute significantly to outdoor pollution. Significant exposure to biomass smoke can also result from forest fires.

Table 2 Health-damaging pollutants as products of incomplete combustion of solid fuels[11,12,21]

Smoke phases	Characteristics	Mechanism and associated health effects
Particulate	Variety of particulates, different size and composition Respirable size, mean aerodynamic diameter <10 μm (PM_{10}) Fine particles <2.5 μm ($PM_{2.5}$) can be deposited in the lower respiratory tract Organic and inorganic (metals, for example) pollutants can be carried by particulate matter In some cases, carcinogenic pollutants are attached to the particle, for example, higher molecular weight (5-ring and more) polycyclic aromatic hydrocarbons (PAHs) such as benzo(a)pyrene	Cause irritation and oxidative stress (additive to other compounds) producing lung and airway inflammation, hyperresponsiveness, and in long-term exposures airway remodeling and emphysema Reduced mucociliary clearance and macrophage response Carcinogenic
Gaseous	Carbon monoxide (CO)	Binds to hemoglobin interfering with transport of oxygen Headache, nausea, dizziness Low birth weight, increase in perinatal deaths. Feto-toxicant, has been associated with poor fetal growth
	Nitrogen oxides (NO_x)	Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, longer-term exposure increases susceptibility to infections
	Sulfur dioxide (SO_2), mainly from coal	Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, bronchoconstriction
	Hundreds of different hydrocarbons Aldehydes and ketones	Adverse effects are varied, including eye and upper and lower respiratory irritation, systemic effects
	Lower molecular weight (2–4 ring) PAHs	Carcinogenic
	Some of these are classified as carcinogenic: 1,3 butadiene; benzene; styrene, and formaldehyde	

Others possible are arsenic and fluorine from coal combustion.

HEALTH EFFECTS OF SOLID FUEL SMOKE INDOOR POLLUTION

The adverse effects on respiratory health of products of incomplete solid-fuel combustion are summarized in Table 2, which also includes some of the known or proposed mechanisms of damage. Exposure to solid fuel smoke can be lifelong, beginning before birth and early infancy, and continuing during adulthood, especially in women, who are traditionally charged with the task of cooking. Exposure is longer in cold communities that require fire-related heating, and may adversely impact lung growth and development, both directly and through an increase in lung infections.

Indoor air pollution from indoor burning of solid fuels has been associated with an increased risk of several diseases and health conditions (Table 3). In general, studies are scarce, and show varied health outcomes. Moreover, they commonly lack a quantitative exposure assessment, and rely instead on qualitative or semiquantitative indicators, such as the use of open fire indoors. The majority of relevant associated diseases[19] are acute respiratory infections and chronic bronchitis in childhood and chronic obstructive pulmonary disease (COPD) in women in developing countries. The amount of time that children and/or women spend in proximity to fires is the crucial determinant of the health impact of indoor air pollution.[20] For other health outcomes, the adverse effects of exposure to solid fuel smoke from coal or biomass

Table 3 Respiratory diseases associated with solid fuel use

Health outcome	Meta-analysis RR (95%CI)[19]*
Strong evidence†	
Acute lower respiratory infection (ALRI) in children <5 years of age in developing countries	2.3 (1.9–2.7) 1.78 (1.45–2.18)[23]
Chronic obstructive pulmonary disease (COPD) in women >30 years of age, mainly homemakers residing in rural areas of developing countries	3.2 (2.3–4.8) 2.14 (1.78–2.58)[18]
Lung cancer (coal smoke exposure) in women >30 years of age	1.9 (1.1–3.5)
Moderate evidence‡	
COPD in men >30 years of age	1.8 (1.0–3.2)
Lung cancer (coal-smoke exposure) in men >30 years of age	1.5 (1.0–2.5)
Lung cancer (biomass smoke exposure) in women >30 years of age	1.5 (1.0–2.1)
Asthma in children aged 5–14 years	1.6 (1.0–2.5)
Asthma, >15 years of age	1.2 (1.0–1.5)
Tuberculosis, >15 years of age	1.5 (1.0–2.4)
Insufficient evidence§	
Upper airway cancer	
Low birth weight and perinatal mortality	
Cardiovascular diseases	

* Meta-analysis results from reference 19, unless otherwise stated.
† Strong evidence: Some 15–20 observational studies for each condition, from developing countries. Evidence is consistent (significantly elevated risk in most, although not in all, studies); the effects are sizable, plausible, and supported by evidence from outdoor air pollution and smoking.[19]
‡ Small number of studies, not all consistent (especially for asthma, which may reflect variations in definitions and condition by age), but supported by studies of outdoor air pollution, smoking, and laboratory animals.[19]
§ Insufficient for quantification based on available evidence.[19]
RR = relative risk; CI = confidence interval.

is expected, as from exposure to tobacco smoke, but information is lacking or scarce about other consequences such as low birth weight and adverse perinatal outcomes (stillbirth).[21] Biomass smoke in Guatemalan women has been shown to increase diastolic blood pressure.[22]

Respiratory infections

Smoke inhalation alters several mechanisms of lung defense, including the efficacy of both the mucociliary escalator and the macrophage function.[11] Exposure to biomass smoke has been clearly associated with an increase in the severity of respiratory infections in children,[23] a notorious cause of disease and death in developing countries. Furthermore, the risk of pneumonia in young children is increased by exposure to solid fuels by a factor of 1.8.

Several studies also found an increased risk of tuberculosis in those exposed to biomass stoves, although such studies are scarce and the results mixed.[24] Biomass smoke exposure is likely only one of the important mechanisms by which poverty increases the incidence of respiratory infections and tuberculosis (Figure, Table 3).

Chronic bronchitis and chronic obstructive lung disease

Women who cook with solid fuels have increased respiratory symptoms, including chronic cough and phlegm, a decrease in lung function,[25] and an increased incidence of COPD,[26,27] which resembles cigarette smoking-related COPD both clinically and in its prognosis.[28,29] However, tobacco smoking tends to give rise to COPD with more emphysema and goblet cell hyperplasia, whereas domestic exposure to wood smoke tends to produce COPD with more small airway fibrosis and anthracosis, and hyperplasia of the pulmonary artery intimal.[30] The typical patient with biomass-smoke-associated COPD is an elderly woman born in a rural area with lifelong exposure to wood smoke, who has mild to moderate airflow obstruction and normal or nearly normal pulmonary transfer factor of carbon monoxide (TL_{CO}) and whose chest X-ray shows mainly bronchial wall thickening. Hypoxemia can be important, especially in communities at moderate or high altitude, or in elderly or obese women. Treatment should be as for COPD in smokers, insisting on the reduction of exposure.

Other respiratory diseases

Tobacco smoking has been strongly associated with several respiratory diseases, and a similar association with biomass smoke has been studied, with limited success. Approximately 10–15% of lung cancers occur in subjects who have never smoked.[31] Coal-smoke exposure is now considered by the International Agency for Research on Cancer (IARC) as a carcinogen (Group 1) in never smokers, whereas exposure to biomass smoke is considered in Group 2 as probably a human carcinogen.[32] Although evidence is limited, biomass smoke has substantial concentrations of known carcinogens, such as polycyclic aromatic hydrocarbons, benzo[a]pyrene, formaldehyde, and benzene, with mutagenic and genotoxic effects.[11,32] In a recent study, exposure to biomass smoke was associated with hypopharyngeal cancer.[33]

Exposure to solid fuel smoke may act as an asthma trigger, but in addition exposure to biomass smoke has been associated with an increased prevalence of asthma.[34,35] Tobacco smokers are more likely than non-smokers to develop several interstitial lung diseases, including idiopathic pulmonary fibrosis, Langerhans cell histiocytosis, desquamative interstitial pneumonia, and bronchiolitis-associated interstitial lung disease. However, an association between solid fuel smoke exposure and interstitial lung disease has been evaluated in only a few studies,[12,36] which have led to reports of reticulonodular opacities in the chest roentgenogram in individuals exposed not only to biomass smoke but often also to inorganic dusts.[36]

BURDEN OF DISEASE

According to World Health Organization estimates, worldwide exposure to solid fuel smoke produces 1.6 million deaths yearly, 693 000 due to COPD and 910 000 due to acute lower respiratory infections (ALRI), as well as 38.5 million disability adjusted life years (DALYs), most due to ALRI, being the eighth overall cause of DALYs in the world and the eleventh cause of death.[19] This is likely an underestimation, as only diseases with a strong evidence base, i.e., COPD, ALRI, and lung cancer from coal burning, are considered (Table 3).

INTERVENTIONS

The use of biomass fuels in developing countries is likely to remain stable or even increase in the near future, as few rural families can afford a fuel that is higher on the energy ladder, such as liquefied petroleum gas or electricity, which are cleaner but more expensive. Also, for cultural reasons, the combined use of biomass with modern fuels is widespread, according to a ‘multiple fuel model’ of development.[37] One approach to reduce the health burden related to biomass fuel has been the provision of low-cost, improved wood-burning stoves in rural areas of developing countries.[14] These relatively simple and cost-efficient technologies can double the energy efficiency of their ‘traditional’ counterparts and reduce indoor pollution. Factors determining the success of these interventions and long-term use in the community involve complex interactions of technological, behavioral, economic, and infrastructural factors. Empirical research may provide technological interventions that are robust with regard to cultural tradition and behavioral factors.

The Chinese National Improved Stoves Program has reported the installation of more than 180 million stoves in rural households since the early 1980s,[17,38] and a retrospective cohort study showed that the incidence of both lung cancer and COPD has decreased over time since stove improvement.[38] A program in India (Improved Chulhas) was initiated in 1983, but required adjustments and has been replaced by a new program, the National Biomass Cookstove Initiative, intended to provide cleaner, more efficient biomass-fueled stoves in rural communities.[17,39]

Community intervention trials using efficient wood stoves are the best way to separate exposure to solid fuel smoke from poverty when evaluating potential health effects. Two recent examples of such trials are the use of the Plancha stove in Guatemala[40] and the Patsari stove in Mexico.[41] Compared with open fires, the Patsari stove has been shown, under actual field conditions, to cause average reductions of 70% in indoor air pollution concentrations,[6] of 56% in household fuel consumption,[42] and of 74% in greenhouse gas emissions.[43] Accordingly, use of an improved biomass stove has reduced several adverse health markers, such as respiratory symptoms, sore eyes, and headache among women in Mexico and Guatemala, even after only a short follow-up time.[41,44] In Mexico, a reduced decline in forced expiratory volume in one second (FEV_1) among Patsari stove users (31 ml) compared with open fire users (62 ml) was observed over 1 year of follow-up, a difference similar to what occurs after smoking cessation.[41] Other interventions have been proposed to reduce child exposure to indoor air pollution, including stove maintenance practices, increasing house ventilation while a fire is burning, reducing the time that children spend close to burning fires, and reducing the duration of solid-fuel burning.[45,46]

FUTURE DIRECTIONS

Indoor pollution will continue to be an essential field for health studies and interventions, because exposure to varied indoor substances will likely increase in coming years. Better studies dealing with genetic susceptibility to indoor pollutants, their carcinogenic effect and their impact on lung growth, lung development and, later on, lung aging, are also required. To answer several of these questions, longitudinal studies are required. A formal evaluation of improved stove programs from many viewpoints is also essential to improve guidance for countries and communities as they implement their own programs. Although local adaptation of programs will always be required, improved biomass stoves will likely be more common, with better community acceptance, reduced burden on forests, and increased spare time for homemakers.

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RÉSUMÉ

La pollution domestique est importante pour la santé car les gens passent la plus grande partie de leur temps à l'intérieur. La moitié de la population mondiale, principalement dans les zones rurales des pays en développement, est exposée à des concentrations élevées de fumée de carburant solide (biomasse et charbon) qui est produite dans des feux ouverts inefficaces. Les concentrations des particules dans les cuisines augmentent jusqu'à la limite de milligrammes par mètre cube au cours de la cuisson. La fumée de carburant solide comprend la majorité des toxines existant dans la fumée de tabac et a été elle aussi mise en association avec toute une série de maladies telles que la bronchopneumopathie chronique obstructive chez les femmes, l'infection respiratoire aiguë chez les enfants et le cancer du poumon chez les femmes (pour autant qu'elles aient été exposées à de la fumée de charbon). D'autres maladies associées à la fumée de tabac, telles la tuberculose, l'asthme, le cancer du tractus respiratoire et les maladies pulmonaires interstitielles, peuvent être également en association avec l'inhalation de fumée de carburant solide, mais les preuves en sont limitées. Comme les modifications souhaitables vers des carburants propres sont peu probables, on a fait des efforts pour utiliser des poêles à bois ou à charbon efficients et ventilés, avec des succès variables dus à leur acceptation inégale par la collectivité.

RESUMEN

La contaminación doméstica es relevante para la salud, ya que pasamos la mayor parte del tiempo intramuros. La mitad de la población mundial se expone a altas concentraciones de humo de combustibles sólidos (carbón mineral y biomasa) que se produce en fogones abiertos ineficientes energéticamente, principalmente en las zonas rurales de países en desarrollo. Las concentraciones de partículas en las cocinas pueden encontrarse en niveles de miligramos por metro cúbico al cocinar. El humo de combustibles sólidos tiene la mayoría de los tóxicos del humo de tabaco y de manera similar se ha asociado a varias enfermedades como la enfermedad pulmonar obstructiva crónica en mujeres, las infecciones respiratorias en niños y el cáncer de pulmón en mujeres (expuestas a carbón mineral). Otras enfermedades del tabaquismo también se han asociado a la exposición a humo de combustibles sólidos, pero la evidencia es escasa: tuberculosis, asma, cáncer del tracto respiratorio y enfermedades intersticiales del pulmón. Como el cambio a combustibles limpios es poco probable, los esfuerzos se han centrado en el uso de estufas eficientes con chimenea, con un éxito variable, debido a que la aceptación comunitaria es heterogénea e inconsistente.