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Indoor Air Pollution: A Review on the Challenges in Third World Countries

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ABSTRACT

BACKGROUND: The challenges of third-world countries toward curbing indoor air pollution seem insurmountable as its solution is closely linked to their economic incapacities, lifestyle, and existing outdoor air quality. The economic incapacities include types of the cookstove, fuel sources, types of insecticides and pesticides, building patterns, indoor fermentation activities (such as leaving dirty plates and biological waste in the house for a long time), and regulation on the use of deodorants. Aside from the common pollutants from these sources, the reactive chemistry of pollutants leads to other kinds of pollutants which have been reported to be short-lived but dangerous.

OBJECTIVES: The objectives of the study are to: profile emerging indoor pollutants; examine the pollutant dynamics and their impact on unplanned regions of developing countries; offer solutions to curb indoor pollution in the identified region; elaborate on the cost analysis of existing solutions and how irrelevant they may be due to the rising poverty index; and project how government policies could help in reducing indoor pollution.

DESIGN: This paper is a review that wholistically examined indoor pollution. A total of fifty-six articles was reviewed in addition to the data obtained from MERRA-2.

RESULTS: The study observed that indoor air pollution dynamics are more complex—compared to outdoor air pollution. It was observed that the possibility to control indoor air pollution is based on the type of pollutants, the reactive chemistry of the pollutants, and ventilation in the building. This review shows that poverty is one of the many reasons why indoor air pollution would be a source of menace for a long time in third-world countries. Several solutions to curbing indoor air pollution were considered with a principal focus on cost and availability.

LIMITATIONS: Most experimental results that were used to corroborate postulates were obtained from the literature. The accuracy of those experiments and the sensitivity of the equipment used cannot be verified.

CONCLUSION: The plant-based technique was identified as a perfect solution to indoor air pollution control in third-world countries but the local architecture and lifestyle of most third-world countries constitute a threat to its adoption. It was observed that less than 8% of third-world countries have specific Air Quality Acts which have not been amended for decades. Most third-world countries have a general Environmental Act with air quality as a sub-section in the Act with very low fines for violators. The inclusion of indoor air quality as a vital public health issue in third-world countries is necessary for the preservation of lives and posterity.

KEYWORDS: Indoor, air pollution, pollutants, cost

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Introduction

Respiratory diseases in third-world countries are alarming based on the use of tobacco (Aït-Khaled et al., 2001). Other significant sources of pollution could be from different uncontrolled and unregulated anthropogenic pollutions across various geographical regions of human existence. Since disease is known to be an abnormal condition that negatively affects living organisms and may lead to death or malfunctioning of organs, investigating its source is a native approach to mitigate the source of pollution. In humans, diseases are categorized under three broad terms, that is, infectious, deficiency, and hereditary diseases (including both genetic diseases and non-genetic hereditary diseases). Broadly speaking, respiratory diseases could be caused by lifestyle (i.e. smoking tobacco and staying around tobacco smokers) and exposure to pollutants (particulate matter, radioactive particulates, heavy metals, aerosols, and bioaerosols). In light of the above, respiratory diseases are largely pathological conditions that affect the exchange of gas within the respiratory organs (lungs, trachea, bronchi, pleural cavity, alveoli, bronchioles, the nerves, muscles, nasal cavities, and pharynx) difficult. Respiratory diseases could be chronic obstructive pulmonary diseases, colds, influenza, asthma, emphysema, lung cancer, pulmonary embolism, pneumonia, pleural effusion, chronic bronchitis, cystic fibrosis, and tuberculosis. All these diseases have their associated signs and symptoms. However, all of these diseases may have a general symptom—cough which has to do with the bronchial tree.

Exposure to pollutants is the most dangerous source of respiratory diseases and deaths in third-world countries (OpenLibrary. 2022). According to World Health Organization (WHO), indoor air pollution is referred to as "the world's largest single environmental health risk." In 2018, before the emergence of the COVID-19 pandemic, WHO reported that deaths from indoor air pollution resulted in about 3.8 million deaths (World Health Organization [WHO], 2018). In light of the above, a reduction in fresh air exchange in buildings with a significant increase in indoor pollutants is known as "sick building syndrome." The most common symptoms by inhabitants of such buildings are difficulty breathing, restlessness, headache, blocked sinuses or a runny nose, and drowsiness. Indoor pollutants significantly contribute to the time-weighted exposures which depend on the duration of the inhabitants within the building. Indoor pollutants have chemical and biological properties. With an enhanced understanding of bioaerosols, indoor pollutants can possess both properties. Indoor pollutants include tobacco smoke, formaldehyde, carbon monoxide, benzo(a)pyrene, nitrogen dioxide, radon decay products, chlorinated solvents, asbestos fibers, respirable particles, volatile organic compounds, and bioaerosols. Some of these indoor pollutants (chlorinated solvents, benzo(a)pyrene, chlorinated solvents, and radon decay products) are classified as carcinogens. In developed countries, the concentrations of indoor carcinogens are found to be more than outdoor levels through smoking (CEPA, 2005). In third-world countries, the sources of indoor carcinogenic pollutants may largely be smoking and fumigating using insecticides or pesticides.

Before the emergence of the COVID-19 pandemic, indoor pollutants were largely from household pollution from burning solid fuels for cooking and heating. Other forms of pollution like inhalable particulate matter (PM2.5 and PM10) were rarely discussed because it is seasonal—occur during harmattan. One of the salient discoveries during the COVID-19 pandemic was the emergence of bioaerosols. These types of indoor air pollutants existed with us before the advent of COVID-19. Bioaerosols consist of aerosols with biological components such as metabolites, toxins, or fragments of microorganisms that are ubiquitously present in the environment. Bioaerosol is also referred to as primary biological airborne particles (PBAPs) that are airborne particles from biological sources—ranging from 0.001 to 100 μm in size. Pathogenic or non-pathogenic and viable or non-viable microorganisms can exist in bioaerosol. Another discovery of bioaerosols is their ability to suspend for 1.65 hours for SARS-CoV-1 and 7.24 hours for SARS-CoV-2 in the air (Doremalen et al., 2020). Based on the different pathogenic, carcinogenic, and toxic natures of indoor pollutants. This review seeks to identify and offer solutions to potential sources of indoor pollutants in third-world countries as a way to enhance Sustainable Development Goals (SDG) target 3.9.1.

In this review paper, the objectives are to: profile emerging indoor pollutants; examine the pollutant dynamics and their impact on unplanned regions of developing countries; offer solutions to curb indoor pollution in the identified region; elaborate on the cost analysis of existing solutions and how irrelevant they may be due to the rising poverty index; and project how government policies could help in reducing indoor pollution.

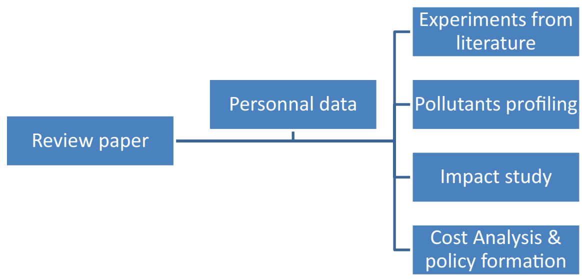

Figure 1. Review chart outline.

Methodology

Based on the objective of the study, the design of the review paper is presented in the chart below (Figure 1). A total of 56 articles were used for this review. The data used by the authors for wind speed analysis were obtained from the MERRA-2 satellite platform for Emure, Southwest Nigeria. Other experimental results discussed were obtained from the literature. Pollutant profiling was done to show new trends and the likely challenges they may pose if not curbed. The impact study was conducted within the spectrum of developing countries. The cost analysis of some solutions was analyzed, and policies from developed and developing countries were examined to understand how the developing countries could reduce indoor pollution via workable and intentional policy formulation.

Indoor Air Pollutants

Indoor air pollutants in third-world countries have been traced to the cooking stoves which are mainly paraffin, natural gas, and propane stoves. In rural areas, firewood, animal dung, palm waste biomass, and charcoal are the main source of solid fuel that releases carbon monoxide, fine particulate matter and black soot as their main pollutants. WEC (2011) reported that over 2.6 billion persons in the world still adapt to this process. IAE (2006) presented the global distribution of biomass cookstove users, however the number might have tripled with the report on biomass stoves market size 2023 to 2030 by BSMAgency (2023). While the rural users are faced with inhalation of carbon monoxide, fine particulate matter and black soot, the urban users that possess improved cookstoves are faced with pollutants from kerosene and propane cookstoves. The propane cookstove emits formaldehyde, carbon monoxide and other harmful pollutants into the air. Kerosene cookstove releases considerable amounts of fine particulate matter (PM2.5 and PM10), carbon monoxide, nitric oxides, sulfur dioxide, formaldehyde, and polycyclic aromatic hydrocarbons (PAHs). The carcinogenic nature of the components of

Table 1. Component of Indoor Pollutants From Insecticide and Pesticide.

S/N	TYPE OF PESTICIDE	ACTIVE INGREDIENT	REFERENCE
1.	Organochlorine	Lindane	Martine't Mannetje (2020)
		Dichlorodiphenyltrichloroethane	
		Dieldrin, aldrin metabolized to dieldrin	
		Heptachlor	
		Mirex	
		Chlordane	
		Endosulfan I	Fernández-Bringas et al. (2008)
		Endosulfan sulfate	
		Heptachlor	
		Methoxychlor	Adeleye et al. (2019)
2.	Organophosphate	Parathion	Martine't Mannetje (2020)
		Chlorpyriphos	Abdulahi et al. (2016)
		Chlorpyrifos	
3.	Polychlorinated camphenes	Toxaphene	Martine't Mannetje (2020)
4.	Pyrethroids	Cyhalothrin	Abdulahi et al. (2016)
		Cypermethrin/Acetamiprid	
		Beta-Cyfluthrin/Imidacloprid	
5.	Organophosphate/Pyrethroids	Profenos/Cypermethrin	Abdulahi et al. (2016)

kerosene is causative factor of cancer (Lam et al., 2012). Based on the duration of cooking which is about 3 to 6 hours daily, the flight duration of pollutants may be 3 to 10 hours. This analysis means that inhabitants and visitors to such buildings are at risk of inhaling noticeable concentrations of pollutants. This information further corroborates the statistics of cancer patients in urban and rural settlements (Li et al., 2018). In summary, a rough estimation shows that indoor air pollution from cooking devices is the major source of pollution.

In third-world countries, fumigation is based on user discretion. With over 2 million deaths from mosquitoes as reported by World Health Organization (WHO) from 2000 onwards, the Institute of Health Metrics and Evaluation (IHME), and the Global Burden of Disease (GBD) from 1990 onwards (Roser & Ritchie, 2022), the sales of insecticides in geographical regions are incredibly high to the impact of malaria around the globe (Hay et al., 2004). Aside from the known dangers of mosquitoes, some other insects and pests constitute a huge risk to the populace of developing countries. Insecticides or pesticides have two main ways of becoming indoor air pollutants, that is, volatilization and aerosolization. These pollutants are retained in the atmosphere as long as there are other particulates in flight.

The properties of insecticides or pesticides sold in the market have a considerable amount of carcinogen (Table 1). With these active ingredients in the indoor atmosphere, infant and maternal mortality or complications are inevitable.

Wood smokes are a source of (polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) such as formaldehyde) indoor pollution. The same effects are seen for indoor particulate matter whose sources are the cooking stove, fireplaces/chimneys, and local bush lamps. VOC from these mentioned sources has adverse effects on the pulmonary health vulnerable of pregnant mothers and infants. Harrison et al. (2019) investigated the individual exposures to VOCs (in μg/m^3) and PAHs (in μg/m^3) with a salient discovery that insecticides contain high concentrations of Toluene, chrysene, m-xylene, 1,2,4-trimethylbenzene, and Benzol. The concentrations for home and workplace were measured simultaneously. It was reported that home pollutants are the dominant individual contributor to personal exposure. Munyeza et al. (2019) reported that the concentration of indoor PAH in parts of Burundi as 1 to 43 μg/m^3. Agbo et al. (2022), investigated the VOCs in urban and rural setting of Nsuka, Nigeria. They reported that the indoor VOC in the urban and rural center are 115 to 254 and 145 to 324 μg/m^3, respectively. Han et al. (2022) reported an indoor PAHs in India to be about 2.5 μg/m^3.

Indoor air pollution from environmental tobacco smoke has been reported severally to be the major contributor to indoor air pollution owing to lifestyle. Tobacco components which are largely polycyclic aromatic hydrocarbons (PAHs) have caused deaths for smokers and people living with them. WHO reported that tobacco smoking led to more than 8 million deaths per year, that is, about 7 million deaths from direct smokers and about 1.2 million deaths of non-smokers being exposed to second-hand smoke (WHO, 2022).

Another source of indoor pollutants is building materials. Several scientists had reported the existence of radon in building materials (Cosma et al., 2013; Khalid et al., 2014; Rafat, 2015). Radon is a common indoor air pollutant from building materials. The building materials are soil, tiles, asbestos, roofing bricks, and rocks used for the foundation of the building. Also, many buildings have been built on radon-emitting rocks. Radon is naturally invisible, odorless, and tasteless gas that seeps up through the ground, walls, and roof into the air. The radioactive decay of radon yields short-lived progeny that attaches to dust and emits alpha, beta, or gamma particles. When these types of particulates are inhaled into the lungs may cause prolonged diseases or deaths. Asbestos used for roofing purposes is sourced from mineral rocks. After prolonged use in the house, it releases dust particles that are inhaled by the inhabitant of the house. The time-exposure factor of asbestos particulates is huge and ultimately leads to respiratory diseases (lung cancer and mesothelioma), heart failure, and death.

Health Implication of Indoor Pollution

WHO reports deaths from indoor air pollution is alarming and the information from the types of indoor pollutants are clear evidence that deaths from indoor air pollution will continue except drastic decision is taken by governments of third world countries. WHO reported that out of the 32% of deaths from ischemic heart disease, 12% are related to indoor air pollution; 23% of deaths from stroke, 21% of lower respiratory infections are ascribed to indoor air pollution; 44% of all pneumonia deaths in children less than 5 years old are ascribed to indoor air pollution; 22% of all adult deaths to pneumonia deaths are ascribed to indoor air pollution; 23% of all deaths due to chronic obstructive pulmonary disease (COPD) in adults in low- and middle-income countries are ascribed to indoor air pollution; 11% of all adult deaths from lung cancer are traced to the carcinogens from indoor pollutants (WHO, 2018).

Respiratory diseases and disorders in the human body can be infectious or chronic. In either case, indoor pollutants have a significant impact on existing or new cases of respiratory diseases or disorders. Scientists have reported the possibility of bacterial or viral infections that could replicate depending on prevalent situations (Thomas & Boma, 2023). For example, a smoker, in addition to the replication of the bacterial or viral cells or tissues would experience chronic obstructive pulmonary disease (COPD) which can be chronic bronchitis and emphysema. The general symptoms in these cases are short breath then onto more complicated occurrences. It is not always the case that the constriction of the bronchiole tubes via excess mucus production is only asthma-related, most time the accumulation of indoor pollutants in the lung could lead to an inevitable restriction of airflow into and out from the lungs. There may also be the rare case that the bacterial or viral infection from indoor pollutants inflames the mucous membranes and lead to the blockage of the sinus openings. The continuous blockage of the sinus opening prevents the mucus from draining.

Wheatley et al. (2011) distinctively illustrate the state of a healthy person via its diffusing capacity for oxygen. When a man is resting, the diffusing capacity for oxygen is 21 ml/min/mmHg and about 20 ml/minute/mmHg when he is awake. However, under strenuous exercise when the pulmonary blood flow and alveolar ventilation increase, the diffusing capacity for oxygen is about 65 ml/minute/mmHg. When the diffusing capacity for oxygen is altered, then there may be respiratory disorder or disease.

Statistics of deaths due to indoor air pollution around the globe are presented in Figure 2. It is observed that most countries that are affected are third-world countries. For example, various researchers in parts of Nigeria (Adeniyi et al., 2016; Gbadero et al., 1995; Salako & Sholeye, 2012) have reported the rampant nature of indoor air pollution in health centers and hospitals.

At Federal Medical Centre (FMC), Owo-Nigeria in southwestern Nigeria. There was a report of the admission of 501 patients into the medical wards with cases relating to respiratory disorders or diseases. The statistics show that diagnoses of different diseases or disorders, for example, 178 (35.5%) patients had pulmonary tuberculosis, 106 (21.1%) with pneumonia, 42 (8.4%) patients with bronchial asthma, and 69 (13.7%) patients with COPD. Other respiratory conditions that were documented include bronchogenic carcinoma 7 (1.4%), pleural effusion 6 (1.2%), upper respiratory tract infection (URTI) 5 (1.0%), and lung abscess 1 (0.2%). In another southwestern state of Nigeria, that is, Federal Medical Centre in Ido-Ekiti, Nigeria. The report showed that out of 183 patients, 77 (42.1%) patients were with pulmonary tuberculosis, 32 (17.5%) patients were with asthma, 28 (15.3%) patients were with pneumonia, 21 (9.8%) patients were with COPD, 4 patients (2.2%) were with unexplained cough, and 1 (0.6%) patient was with lung cancer (Adeniyi et al., 2016).

In south-south Nigeria—University of Calabar Teaching Hospital Calabar where 325 patients were diagnosed with different respiratory orders or diseases, for example, 217 (66.8%), 81 (24.9%), 16 (4.9%), 7 (2.2%), and 2 (0.6%) patients had pulmonary tuberculosis, pneumonia, asthma, COPD, and lung cancer respectively (Salako & Sholeye, 2012). In the north-central parts of Nigeria, that is, University of Ilorin Teaching Hospital (UITH) Kwara State. The report showed that out of 7012 children admitted, 1939 (27.7%) patients were due to respiratory diseases. About 1,320 (68.1%), 196 (10.1%), and 147

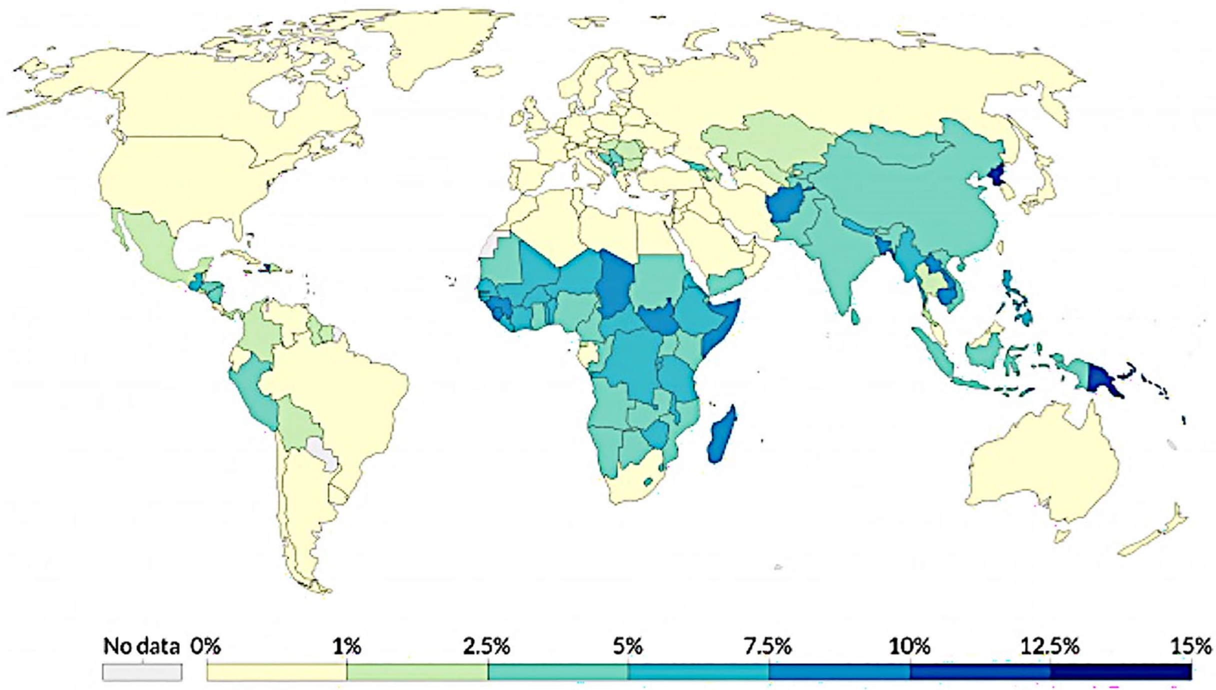

Figure 2. Deaths due to indoor air pollution around the globe (Roser & Ritchie, 2022).

(7.6%) of the patients had pneumonia, pneumonitis, and tuberculosis, respectively. The other patients had one form of respiratory disorder. In the southeastern part of Nigeria, that is, Children Emergency Unit of the University of Nigeria Teaching Hospital (UNTH), Ituku/Ozalla, Enugu, Nigeria. The report showed that out of the total of 8,974 children admitted, 2214 (24.7%) patients were due to respiratory diseases with 753 (34%) and 613 (27.7%) patients diagnosed with pneumonia and acute bronchial asthma respectively (Oguonu et al., 2014). Other cases were respiratory disorders.

Indoor Air Pollution Models

Indoor air pollution models are found to be increasingly reliable for determining individual and population exposure to different forms of air pollutants. It could be used for sorting out trends in experimental data. Models are important because they are cheaper as laboratory and field testing is costly, time-consuming, and technically challenging to preempt indoor conditions. However, most of these models are due for system revision as new pollutants keep emerging across the globe. Hence, at the current stage, data generated from old indoor air pollution are error-prone. These models can be numerical models, mass-balance equations, or computational models. Most computational models incorporate the use of big data analytics, as well as machine learning techniques to achieve high precision.

Before now, models considered a few parameters like generating rates, infiltration rates, indoor source strengths, pollutant decay rates, the lifespan of pollutants, duration of the particulate flight, deposition rate, and mixing factors. After model formulations, it is validated using a live dataset to know the degree of accuracy. In most cases, the live dataset may give information on pollutant concentrations, exposure time, and mobility with time. Most time mathematical models are adopted to extrapolate other key parameters such as generating rates, infiltration rates, indoor source strengths, pollutant decay rates, the lifespan of pollutants, duration of the particulate flight, deposition rate, and mixing factors. At another time structured methodologies are used to determine most parameters so that other parameters can be derived from existing parameters.

One of the notable indoor air pollution models is the fixed station sampling where the theories gathered from the outdoor air quality dataset are used for indoor air pollution analysis. In reality, the characterization conditions for outdoor air pollution differ from the indoor air pollution, but the inclusion of certain parameters (such as type and concentration of pollutants, rate of air exchange, air volume inside the building, ventilation, source, and sink parameters) are used to redefine or recalibrate the indoor protocols. A good example of this type of model is the Long-range Energy Alternative Planning (LEAP)—Integrated Benefits Calculator (IBC) which is used both for outdoor and indoor air pollution. The IBC is used to evaluate the impacts of outdoor air pollution while the Household Air Pollution Intervention Tool (HAPIT III tool) is used to study indoor air pollution. The sampling techniques are continuous and "real-time" sampling. Continuous sampling provides an average sampling over a specified period while "real-time" sampling is taken at a specified time interval or period. One of the advantages of fixed station sampling is the flexibility to keep sampling equipment at remote locations, that is, inside or outside the building.

The integrated exposure-response (IER) model for estimating the relative risk of PM2.5 pollutants. The model works with relative risk and long-term exposure to PM2.5 from four different sources, that is, ambient air pollution, active smoking, second-hand tobacco smoke, and household air pollution. The IER model is listed below (Burnett et al., 2014):

$$IER_{Model} = 1 + \alpha\left(1 - \exp\left[-\gamma\left(y - y_o\right)^{\delta}\right]\right), y \geq y_o$$
$$IER_{Model} = 1, y < y_o \quad (1)$$

y_o is the counterfactual concentration of PM2.5, and y is the exposure to ambient PM2.5. α, γ, and δ are parameters based on live data to estimate relative risk. Emetere and Ojo (2020) derived the indoor bioaerosol transport as given in equation (2).

$$C = \frac{m \times wf \times cf \times d \times 4k\alpha}{UR}\left(\frac{3\beta}{2} - \frac{\beta}{2}e^{k\left(t - \frac{1}{2\alpha}\right)} + \left(\frac{\beta}{2} - e^{-k\left(t - \frac{1}{2\alpha}\right)}\right) \times H(t)\right) \quad (2)$$

where $C(t)$ is the emission rate at time t (mg/minute), M is the mass of the product, WF is the weight fraction of chemical in the product (unitless), D is the atmospheric dilution, α and β are parameters gotten by measurement, CF is the Conversion factor (hour/60 minute), k is the first order rate constant for emission decline ($minute^{-1}$), t is the time, and $H(t)$ is the time condition.

Other mathematical indoor air pollution models include the finite difference method, finite volume method, finite element method, boundary element method, particle-in-cell, meshless methods, and Lagrangian particle transport. A known empirical model for indoor air pollution is the receptor model which includes the chemical mass balance model, multivariate model, and microscopic model (Watson et al., 1988).

The future of indoor air pollution models is the influence of outdoor air pollution in its formulation. A typical example of this reality is the COVID-19 pandemic where indoor transmission is enforced by aerosolization of the virus. Hence, outdoor pollutant levels have a direct influence on indoor ventilation (Ahmad et al., 2016). Figure 3 corroborates this assertion below. The variation between the indoor and outdoor pollutants concentration is established. The projection for the outdoor and indoor pollution shows that Acute lower respiratory infections (ALRI) and chronic obstructive pulmonary disease (COPD) are expected to increase linearly by 2024. Stroke is expected to drop in the outdoor while it will slightly increase indoor. The projection for the outdoor and indoor pollution shows that ischemic heart disease (IHD) is expected to drop slightly.

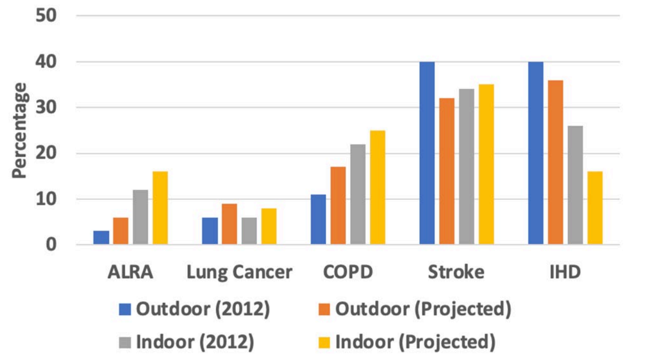

Figure 3. WHO derived outdoor and indoor air pollution in 2012 and projection for 2024.

Due to energy challenges in third-world countries, indoor ventilation is enhanced by outdoor wind flows which are a source of pollutants into the confines of the building. An illustration of this fact is demonstrated by the wind dynamics in one of the southwestern States in Nigeria-Emure in Ekiti state. The sustainable test was carried out using the average decal wind speed to see the likely pattern over four decades (Table 2). Three patterns were observed in the averages of wind speed within four decades. The first pattern was a positive parabola whose minimum was found between 1990 and 1999 (i.e. April). The second pattern was a consistent increase in average wind speed within four decades (i.e. May). The third pattern is the inconsistent data spread across the monthly averages of January, February, March, June, July, August, September, October, November, and December.

The sustainability of domestic wind energy generation was investigated using the wind speed averages as presented in Table 1. It was observed that two patterns could be seen in the average wind speed for each decade. The first pattern (i.e. September) is the consistently decreasing wind speed over four decades. The second pattern dismal variation of wind speed across the four decades. These results show that the consistency of the average wind flow is 0%, maximum power generation is 0%, and reliability is 8%. Consistency percentage illustrates known patterns within the years; maximum power generation is the months with a consistent increase within four decades; reliability is months that have shown a 75% of increase within four decades. These results show that the consistency of about 2 m/s has the same infiltration of outdoor pollutants into the indoor environment in the building as the inhabitants expect fresh air for ventilation. The seasonal influence of the wind system is presented in Figure 4(a) and (b).

Complex Dynamics of Indoor Air Pollution

The dynamics of indoor air pollutants within a building are more complex than outdoor air pollution that have several ventilation routes. The indoor is a partial close system. Based upon this fact is the postulation of mass conservation to understand the dynamics of indoor air pollutants. For a hypothetical single room, the equation is given as (Terrain & Canyons, 1988):

Table 2. Decade Average Wind Speed.

	WIND SPEED (M/S)	WIND SPEED (M/S)	WIND SPEED (M/S)	WIND SPEED (M/S)
Month	1980–1989	1990–1999	2000–2009	2010–2018
January	236,805	22,6425	222,399	269,653
February	240,043	231,518	219,608	257,743
March	242,765	234,241	224,965	247,027
April	23,238	229,922	239,359	242,127
May	218,458	220,792	228,008	230,288
June	228,154	200,662	211,504	224,596
July	243,576	222,767	22,677	210,857
August	227,763	23,191	228,309	181,918
September	231,693	237,458	223,495	198,304
October	230,561	222,642	224,695	208,512
November	220,767	229,215	221,369	211,901
December	244,917	227,824	212,848	250,673

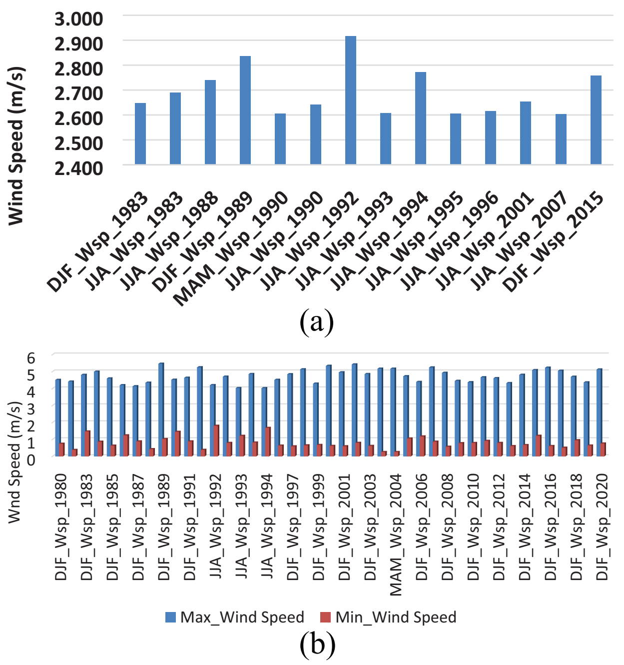

Figure 4. (a) Profile of highest values of wind speed mean between 1980 and 2020 and (b) profile of highest values of wind speed maximum and minimum between 1980 and 2020.

$$V\frac{dC}{dt} = QC_a + E - QC - kCV$$

Where V is the volume of the room, QC_a is the rate of pollutants entering the building from outdoors, E is the emission rate from the indoor source (e.g. cookstove), QC is the rate of pollutants leaving the building by leakage to outdoor, kCV is the rate of pollutant leaving the building by decay, k is the decay rate, C is the indoor air pollutant concentration within the building, and C_a is the outdoor pollutant concentration.

However, there are several factors that question the accuracy of this hypothesis. The factors include components in the building, the structure of the building, air resistance in the building, ventilation routes in the building and number of occupants. In other words, the concept of mass conservation to explain the dynamics of indoor pollutants may be accurate on a laboratory scale but not close to accuracy in a live situation. Nazaroff (2004) listed essential factors for understanding the dynamics of indoor pollutants as indoor air pollutant emissions, outdoor-indoor ventilation route, filtration and pollutant deposition within the building. The size of pollutants plays a significant role in the dynamics. USEPA (2022a) reported that pollutants less than 10 µm in diameter pose problems to humans and animals as they travel deep into the lungs with some fractions diffusing into your bloodstream. Air particles are categorized by their diameter. Hence, three size modes exist, that is, ultrafine (0.1 µm), accumulation (0.1–2 µm), and coarse (⩾2 µm). The sizes of bioaerosols are most times smaller than ultrafine particles. For example, its size scale ranges from about 15 to 400 nm for viruses, 0.03 to 1 nm for bacteria to 0.1 to 10 nm for fungal spores, pollen, plant debris etc. Bioaerosols can cause adverse effects on humans, animals, and plants because of their size to travel into the lungs and pathogens to create specific respiratory infections (Wittmaack et al., 2005). The aerodynamic size and fluorescence properties of bioaerosols can be used to detect their presence in a location. The sizes of bioaerosols found indoors and their corresponding sizes are listed in Table 3. The possibility of the characteristic changes of

Table 3. Properties of Indoor Bioaerosols (Yu & Mui, 2017).

BIOAEROSOL SPECIES	ATCC NO.	RELATIVE ABUNDANCE	BIOAEROSOL DIAMETER (μM)	ASPECT RATIO
(a) Bacteria				
Aeromonas hydrophila	—	<1%	1.8	2.9
Bacilus atrophaeus	9,372	1%–19%	1.1	2.2
Campylobacter jejuni	—	<1%	2	3.1
Escherichia coli	10,536	<1%	1	1.7
Micrococcus luterus	4,698	9%–76%	0.7	1.1
Salmonella typhimurium	14,028	<1%	1.5	3.2
Serratia marscens	6,911	<1%	2.6	6.9
Staphylococcus aureus	—	5%–10%	0.69	1.0
(b) Fungi				
Penicillium citrinium	9,849	8%–34%	2.5	1.1
Altermaria alternate	6,663	0%–4%	3	1.4
Aspergillus niger	—	9%–20%	3	1.2
Cladosporium cladosporidies	16,021	17%–22%	3.4	2.1
Rhizopus spp.	—	0%–2%	8.6	1.0

Table 4. Lifespan, Sizes, and Morphology of Indoor Pollutants.

POLLUTANT	LIFESPAN	SIZE	MORPHOLOGY
CO	60 days	112.8 pm	Molecule
CO_2	300–1,000 years	116.3 pm	Molecule
NO	Half-life: 9–900 minutes	115 pm	molecule
NO2	150 years	119.7 pm	Molecule
Pb	Stays suspended for 10 hours	202	Lead dust
Pollen	4 months	25 μm	Numerous
Mold	Indefinite	3–40 μm	Molds

bioaerosols had been proven by Dong et al. (2022). The researcher observed that the concentration of bioaerosols increased during the dust events in both the source and deposition regions. This revelation is salient as the bioaerosols in the toilet and nostrils of a sick person in a building can move to all parts of the home. This hypothesis had been corroborated by mathematical/computational simulations in the literature (Emetere & Ojo, 2020; Yu & Mui, 2017).

The sizes and lifespan of selected gaseous and particulate pollutants are presented in Table 4. The gaseous pollutants are more complicated because of their lifespan and inability to deposit on surfaces. Hence, they can be within the building for a long time to create more damage. The concept of reactive chemistry as explained by Weschler and Carslaw (2018) makes indoor air pollution more complicated.

Reactive chemistry is reactive chemicals formed through indoor air chemistry. A typical example of these kinds of chemicals is hydroxyl (OH), hydroperoxy (HO_2), organic peroxy, nitrate (NO_3) radicals, Criegee intermediates (formed from ozone and indoor unsaturated VOCs such as terpenes), nitrated and oxygenated VOCs (such as organic nitrates, carbonyls, dicarbonyls, and hydroxy carbonyls), and secondary organic aerosol (SOA). Sketchy information shows that this type of chemical is short-lived radical species. However, no structured study had been conducted to know its lifespan indoors. All these discoveries make the dynamics of indoor air pollution a complex one. That is the main reason why accidental indoor air pollution is difficult to curb within a short time.

Different studies corroborate that indoor air pollution is difficult to predict or control. Vanker et al. (2017) study on the effect of exposure of infants to indoor air pollution. The study was a three years research work that considered a mother and infant in Paarl, South Africa via installed sensors at every section of the house. The focus of the research was to estimate the impact of lower respiratory tract illness (LRTI) in African infants through pollutants from smoking and other sources such as SO_2, NO_2, PM2.5/PM10, CO, benzene, and toluene. They observed that 23% of the infant were found to have associated LRTI per year. Patients with high toluene pollutant concentration had severe LRTI. On more specific analysis, the research could not extensively show the individual role of pollutants for LRTI in infants. As already, the dynamics of indoor air pollution cannot be known except salient questions on components in the building, the structure of the building, air resistance in the building, ventilation routes in the building and number of occupants are not diligently addressed.

Ba et al. (2019) considered the influence of outdoor and indoor air pollution in Dakar considering individual exposure levels. The pollutants considered in the study were CO, CO_2, NO, NO_2, and PM_{10}. The research target were bus drivers, traders working along the main roads and housemaids. The individual exposure levels of the selected targets were measured using biomarkers. It was reported that housemaids had more exposure than selected targets. Bus drivers and traders were found to be high compared to other targets. The researcher claimed that the housemaid was exposed to a high concentration of indoor benzene—due to indoor activities. The public bus interior was found to be more polluted with PM_{10}, CO, CO_2, and NO than other target locations. It is easy to understand that high pollutants in public buses arise from ventilation in the bus, road structure in town, types of fuel sold and leakages of pollutants from the exhaust into the vehicle. All these factors that raise pollutants concentration are common in the indoors—making it a source of concern technically.

Armah et al. (2015) investigated the pollution from solid cooking fuels via smoke from unprocessed wood in four regions of Ghana and the likely health effects of exposure on selected research targets. They used complementary log-log multivariate models in their study. Their results showed that rural dwellers which were the main user of these kinds of solid cooking fuels were most affected. The demography of the affected was seen to be men and women between the ages of| 25 to 49 years of age. Invariably, the reporter showed that the level of poverty has a direct relationship with the kind of pollutants they are exposed to. For example, they took note that the research targets that had high exposure were the poorest rural populations with no access to electricity. This research shows that poverty is one of the many reasons why indoor air pollution would be a source of menace for a long time in third-world countries.

Mutahi et al. (2021) investigated indoor and outdoor air quality (i.e. PM2.5) in parts of Kenya and how impactful they were perceived in settlements that were categorized as urban and rural. They observed that both the urban and rural settlements showed levels that exceeded the WHO limit. Concentrations of $PM_{2.5}$ and black carbon were observed to be high in indoors than outdoor environments. Also, high lead (Pb) content was found in the deposit samples collected—exceeding the WHO limit. Like the previous researcher in third world countries, air quality condition was worse in rural settlements because of solid cooking fuels (i.e. wood and kerosene) used. This research outcome is odd because if indoor and outdoor air pollutant concentrations exceed WHO limits and indoor was found to have a higher concentration, then there are two possibilities. One of the possibilities affirms the earlier assertion that a building could have poor ventilation and could retain gaseous pollutants for as long as its lifespan. The second possibility was that the sampling technique over the rural settlement may be somewhat faulty as all buildings cannot have the same outcome.

Existing Solutions to Indoor Air Pollution

Indoor air pollution has detrimental impacts on human health, including increased risk of respiratory diseases and asthma episodes, as well as irritation of the ears, nose, and throat. Managing these substances' amounts begins with tracking the particles, chemicals, and gases that make them up. The indoor air quality standards documented by EPA's Air Quality Index are given as 25 ppm limit for an 8-hour for carbon monoxide indoor inhalation, maximum of 100 ppb per hour for nitrogen dioxide inhalation, 250 ppm for methylene chloride inhalation, less than 10 ppm for Polycyclic Aromatic Hydrocarbons (PAHs) inhalation, and 0 to 15 ppm for Volatile Organic Compounds (VOCs).

One of the multiple solutions to curb indoor air pollution is the use of fume/smoke extractors. The installation of fume/smoke extractor in various parts of the building having to do with heating or burning solid fuels are proven ways to reduce indoor pollutants. The list of different types of fume/smoke extractors used in homes to reduce indoor air pollution is presented in Table 5.

However, considering the poverty peculiarity in third-world countries, affording any of these gadgets (displayed above) in individual homes and the corresponding energy required to run them is practically difficult. Bill Gates in one of his memoirs wrote that "the number of people living on less than $2 a day is over 700 million" (Gates, 2019). In 2022, the World Bank reported the list of countries with the highest poverty rates. The first ten countries are South Sudan (82.30%), Equatorial Guinea (76.80%), Madagascar (70.70%), Guinea-Bissau (69.30%), Eritrea (69.00%), Sao Tome and Principe (66.70%), Burundi (64.90%), Democratic Republic of the Congo (63.90%), Central African Republic (62.00%), and Guatemala (59.30%). In other words, adopting anything that looks like technology in third-world countries to curb indoor air pollution is visibly difficult to purchase and operate.

Another possible solution is the provision of clean and affordable domestic fuels. The actual definition of clean domestic fuels is fuels whose emission is within WHO global air quality guidelines of 2021(WHO, 2021). Hence, fuels or heat sources of this category are solar, hydrogen, electric, biogas, natural gas, and ethanol. However, the definition of affordable fuel is relative judging from the poverty peculiarity of each region. For example, Woolley et al. (2022) reported that during the COVID and Post-COVID eras in Rwanda witnessed a change in primary cooking fuel due to affordability. For example, 20 % moved from Liquid Petroleum Gas

Table 5. Cost of Home Fume/Smoke Extractor.

HOME FUME/SMOKE EXTRACTOR	PRICE ($)
Hakko FA400-04 Bench Top ESD-Safe Smoke Absorber	73.88
Plastic Fresh Air Ventilation Kitchen Smoke Extractor	15.2
Greenhouse ventilation box fan	200
POLYGEE Extractor Smoke Cooking Smoke ESP Extractor	659
American Style Restaurant Fresh Air Exhaust Chimney Hood	200
S&P UK 60 cm Kitchen Hood Heat Extractor	160
S&P UK 90 cm Kitchen Hood Heat Extractor	193.3
Manrose 150 mm 6" Extractor Fan	37.3
Manrose 300 mm 12" Extractor Fan	126.6
Vent 6" 150 mm Extractor Fan	53.3
Xpelair GX12 Extractor Fan	166.6
Xpelair GX6 Extractor Fan	51.3
Wall Mount 26" Heat Extractor Fan Three phase	193.3
Digital Kitchen Range Hoods Air Extractor	93.32
Newcastle Digital Kitchen Range Hoods Air Extractor	93.18
Gs 90 cm Plasma Smell, Smoke & Heat Extractor Kitchen Hood	238.7
UC 90 cm Smoke/ Heat Extractor Cooker Hood Stainless	86.5
Newcastle Digitally Smart 90 cm Smoke Extractor Hood Ductless	89.8
90 cm Smoke/Heat Extractor Range Hood 4 Gas Cooker Kitchen	198.54
Digital Smoke Extractor/Cooker Hood	224.6
Manual Smoke Extractor/Cooker Hood	97.3

(LPG) to charcoal, while 46.7% of users moved from charcoal to firewood. The user's perception shows that they had already formed an opinion toward the new life introduced during COVID year. By extension, most third-world countries had their cooking lifestyle changed from clean to polluting cooking fuels. This decision has a significant impact on their local economies as the world experiences a global economic meltdown. The use of electric heating could have been good but grid power generation in Africa has several challenges that cannot be solved unless there is a change of attitude (Emetere et al., 2021). In other words, the solution to low indoor air pollution in third-world countries is the use of solar as a heating source. Africa has a huge advantage looking at Figure 5. Due to the poverty index, three means of cooking -using solar heat sources such as simple fabricated solar cookstoves, using induction cookstoves for photovoltaic (PV) standalone users and thermovoltaics (TV) cookstoves. The cost of these solar heating sources generally ranges from $15 to 89 but most homes cannot afford them except for government and corporate intervention schemes. Fabricated solar cookstoves are constructed from scraps, hence their purchase cost is affordable. However, the disadvantage is that the user may have to cook during sunshine hours. During temporal bad weather such as rainy days, the user may have to depend on other sources of heating. The second disadvantage is the user would have to come to the open—outside his/her house to cook. The second solar cooking option—the induction cookstove for PV users is a special type of electric cooktop that generates its energy from an electromagnetic field below the glass cookstove surface, which then transfers current directly to magnetic cookware, causing it to heat up. The identified disadvantage of these types of cookstoves is the need for users to change their cookware to maximize energy management. TV cookstove has different designs—common and modern TV cookstove. The common type has the same issues as the locally constructed solar cookstove as already illustrated above. The modern TV cookstove uses storage devices that allow it to be used at any time of the day, that is, at the owner's convenience.

Due to the high financial involvement in curbing indoor air pollution in third-world countries, it is essential to note that it is possible to encourage individual routines that could help solve the aforementioned problem. The first solution is having an outdoor garden that has the potential to break the outdoor influx of pollutants into the building. The second solution is growing plants indoors. Several scientists had proven that certain plants are efficient to remove air pollutants indoors. For example, Wolverton et al. (1985) proved that certain higher plants and their associated soil microorganisms can absorb air pollutants. Wolverton and McCaleb (1986) and McCaleb and Bounds (1987) reported that when these air pollutants are absorbed by the plants, its root and associated microorganisms can destroy the biological properties of the pollutants (in the case of bioaerosols) and organic chemicals (in case of air deodorant or insecticide). Based on the above, a NASA sponsored project led by Wolverton et al. (1989) showed a variety of indoor and outdoor plants that can drastically reduce the different types of pollutants. This solution to indoor air pollution is the cheapest and most effective for third-world countries but their local architecture and lifestyle are notable barriers that could be overcome in the long term. Most of the local architecture in third-world countries is characterized by poorly ventilated structures as shown in Figure 6. Destroying and rebuilding houses in such settings would be very expensive in both the short and long term. The second challenge is the lifestyle of not seeing the need to have plants indoors. Some other persons attach cultural myths to indoor plants. For example, Portillo

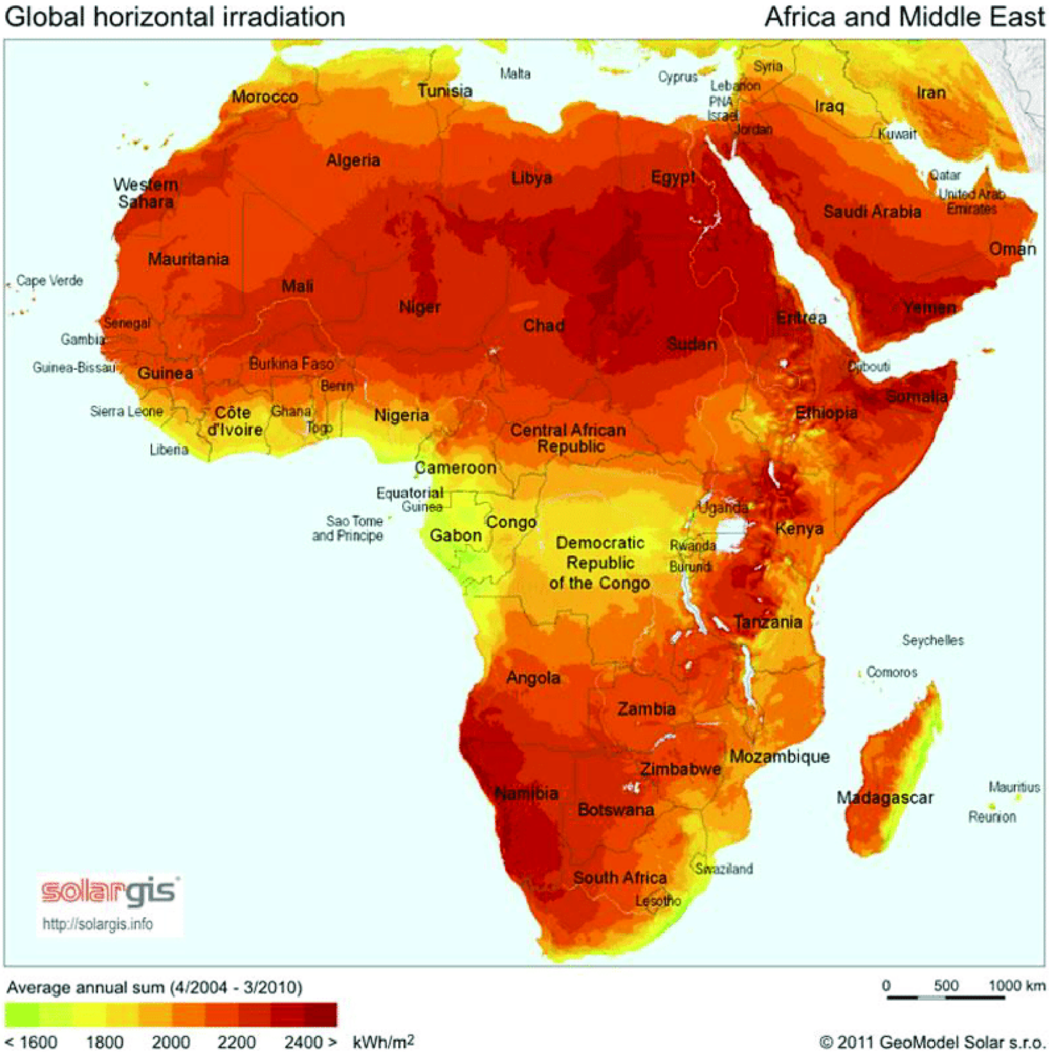

Figure 5. Prospect of solar adoption as a cooking source (GeoSunAfrica, 2013).

Figure 6. Local architecture characterized by poor ventilation in Ecuador (Belsky, 2023).

(2020) reported that some culture believes that indoor plants can bring bad luck.

Need for Policy Review and Enforcement

In this section, policies from developed and developing countries were examined to understand how developing countries could reduce indoor pollution via workable and intentional policy formulation that has been used in developed countries. It has been established from above that indoor air pollution has economic importance. This fact cannot be ascertained by looking at the health cost of the event but by considering other factors like deprivation of source of livelihood during sickness, organization losses due to specific services rendered by a sick employee, losses by transport services, school attendance, and productivity of children of the sick person etc. Unfortunately, literature surveys have proven that there are policies or Acts to curb indoor pollution. Despite the enabling laws, there is still a huge loss from indoor air pollution-related diseases in developing countries. This discovery underscores the need for policy enforcement or revised policy formulation. This section considers the policy review in a developed country and juxtaposes it with third-world countries to highlight areas of weakness.

In the United State of America, there is the Air Quality Act of 1967 and the Clean Air Act (CAA) of 1970 which empowers the US Environmental Protection Agency (USEPA) to regulate air pollutant emissions from stationary and mobile sources. In section 112 of CAA, the definition of hazardous air pollutants and sources of such pollutants was clearly stated. CAA was amended in 1977 to cater to geographical regions that have exceeded the air quality standard detected by the National Ambient Air Quality Standards (NAAQS). In 1990, the CAA was amended with emphasis on section 112 to include regulations on the limits of pollutants that can be emitted from major pollution sources such as chemical companies, mining companies, and factories (USEPA, 2022b). The enforcement of CAA is accomplished by federal, state, and tribal regulatory organs through the different arms of the compliance monitoring program. In 2022, ALTIVIA Petrochemicals LLC in Haverhill, Ohio was one of the companies that were fined $1,112,500 for leak detection and repair work practices (Department of Justice, 2022). Aside from the CAA of 1990 as amended, there is the Indoor Air Quality Act of 1991 which was passed by the 102nd Congress (1991–1992). The act empowers USEPA to assure the quality of indoor air (domestic and occupational), including coordinating and accelerating efforts related to the causes, detection, and correction of contaminated air (Mitchell, 1991). The act was expatiated by USEPA via the definition of indoor pollutants and its acclaimed sources. Like the CAA, the act is enforced by federal, state, and tribal regulatory organs. Aside from the Indoor Air Quality Act of 1991, further Acts and laws have been passed, for example, The Air Quality Amendment Act of 2014. The Act is comprised of new rights for tenants dealing with mold (e.g. bioaerosols in form of fungi, hyphae, mycotoxins etc.) in residential units. The Act mandates landlords to conduct inspection of his/her facility within 7 days when the case is reported to him/her by the tenant. If the source is confirmed, the landlord has 30 days to remove visible indoor mold (Lawhelp, 2016). Aside from these Acts and laws are Prevention of Significant Deterioration (PSD) program, Regional Haze Rule of 1999, National Environmental Policy Act, National Forest Management Act etc.

In Nigeria, the only regulation identified is the National Environmental (Air Quality Control) Regulations 2013 which empowered National Environmental Standards Regulations Enforcement Agency Act (NESREAA) to enforce air quality standards in atmospheric emissions, vehicular emissions, open burning, and refrigeration and air conditioning equipment (RAC). Another law in force is the Harmful Waste Act of 2013 which prohibits the emission of hazardous gases into the atmosphere. The fine for violators is $270 in bulk and $27 per day till the offense is cleared (Sodipo et al., 2017). Unlike the monetary fine USEPA, offenders would deliberately be polluting the air with a minimum fine at the worst encounter which may not occur more than once in a decade. Offenders of China's Air Pollution Control Act 2018 (article 6(1)) pay a fine of $100,000 to $1 million (Environmental Protection Administration, 2018). Monetary fine, it is clear that developing countries are not serious about formulating and enforcing air pollution Acts.

In South Africa, there is the Air Quality Act of 2004 to control emissions from the chimney, compression ignition-powered vehicles, dark smoke, dust, fuel-burning equipment, fumes, mobile source, and non-point source. There is the Air Pollution Control By-law of 2021 which is in force in Gauteng Province. In some other provinces in South Africa, laws on air pollution are engrafted into other environmental acts like Municipal Systems Act of 2000 and National Environmental Management Act (NEMA) of 1998. NEMA was amended under Act 44 of 2008, Act 14 of 2009, Act 14 of 2013, Act 20 of 2014, and Act 2 of 2022. The fine for violators is $217. The same trend as Nigeria. In Kenya, laws guiding air quality were enshrined in the Environmental Management and Co-Ordination Act of 1999 and a modified Environmental Management and Co-Ordination (Air quality) regulations of 2014. The laws were enforced by the Cabinet Secretary for Environment, Water and Natural Resources. Hence, the enforcement of air quality standards by the Secretary is naturally lopsided. The fine for violators is $4055. From the literature survey, Mozambique does not have a specific Act on air pollution. Like Kenya and Nigeria, laws guiding air quality were enshrined in the Environmental Law Act of 1997.

In India, the Air (Prevention and Control of Pollution) Act of 1981 was saddled on the Central Board and State Boards to enforce to prevent, control, or abate air pollution in the country. They assume an advisory role to the government and perform regular inspections of chemical industrial plants, the manufacturing industry etc. One of the successes of the enforcement agency is the indictment of a chemical plant—Union Carbide (India) Limited whose emission led to the death of over 3,000 persons. The fine paid by the company was $470 million to affected families and the government (Republic of India, 1981). The introduction of the Environment Protection Act of 1986 brought stringent fines which are financially and criminally demanding. For example, when a company is found to violate the Act, the owner of the company, management and the company face legal and financial punishment (Sangam, 2017). With the realities of indoor air pollution, there is still the sentiment that indoor air pollution is not a public health concern but is associated with private health bridges (Sundell et al., 2021). In 2022, there is still the intellectual argument that indoor air quality is incorporated into India's primary Air Law (Singh & Dewan, 2022). Since the enactment of the Air (Prevention and Control of Pollution) Act of 1981, it has not been removed.

Only 8% of third-world countries have a specific Air Quality Act which is not amended for over a decade. Most third-world countries have a general environmental Act with air quality as a section of the act. When a general protective requirement is assigned to a generic Act on the environment, the disbursement of funds to enforcing agency is also lumped up. In the end, nothing is achieved as the enforcing agency would by the scale of preference concentrate on one of the tasks per time as funds to execute its activities is usually not adequate. Most of the Acts empower the enforcing agency to make a review of the regulations. For example, in Nigeria, NESREAA was empowered by

Section 8 (1)(K) to make and review regulations on air and water quality. No clear legislative process like the developed countries is seen in the third world countries as regards air quality.

Limitations

This review holistically examined the challenges of indoor pollution in third-world countries. The study came with certain limitations. Most experimental results that were used to corroborate postulates were obtained from the literature. The accuracy of those experiments and the sensitivity of the equipment used cannot be verified. Since it is a review work, all facts that were cited were based on the acceptability of authors who had previously cited the literature. An in-depth evaluation of the facts and postulates highlighted in this work would require massive funds and legal guidance not to infringe on the rights of the homes to be adopted as case studies.

Conclusion

This review had established all the minor but salient issues regarding indoor air pollution in third-world countries. The challenges of third-world countries toward curbing indoor air pollution seem to be identified as economic incapacities, lifestyle, legislative unwillingness and existing outdoor air quality. The economic incapacities were matters surrounding cookstove, fuel source, regulation of insecticides and pesticide, building pattern, indoor fermentation activities, and regulation on the use of deodorants, which were identified as the major that requires conscious investment by government and private organization to overcome. The definition of indoor pollutants, that is, bioaerosols, reactive chemistry of pollutants and emissions from electronic gadgets are disturbing development that calls for the attention of the government for an awareness campaign to reduce deaths from indoor air pollution. It was noted that indoor air pollution dynamics is somewhat complex compared to outdoor air pollution making it very difficult to control in cases of accident. More so due to the ventilation in a building, fine particulate and gaseous pollutants can stay longer in the building where it is expected to find their way into human or animal lungs. The idea of reactive chemistry of the pollutants shed more light on the potential danger when the pollutants are transformed into a different compound that has biological or chemical properties. Looking at the menace of indoor air pollutants at higher concentrations, a possible solution to curbing excess indoor emissions was proposed. The plant-based technique was identified as a perfect solution to indoor air pollution control in third-world countries but the local architecture and lifestyle of the people constitute a threat to its adoption. More so, it will be expensive to demolish buildings to meet up with these discoveries. It was observed that less than 8% of third-world countries have a specific Air Quality Act which is not been amended for decades. Most third-world countries have a general Environmental Act with air quality as a section of the act with very low fines for violators. In conclusion, there is a need for the inclusion of indoor air quality as a public health issue in third-world countries.

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