



## Socioeconomic determinants of indoor air pollution exposure from household cleaning chemicals

 **Fatima E. Al Kuwari**<sup>1</sup>

 **Rima J. Isaifan**<sup>2+</sup>

<sup>1</sup>International Economics Department, School of Foreign Service, Georgetown University, Doha, Qatar.

Email: [fa679@georgetown.edu](mailto:fa679@georgetown.edu)

<sup>2</sup>Department of Environmental Sciences, Cambridge Corporate University, 6006 Lucerne, Switzerland.

Email: [risaifan@cambridge-cu.ch](mailto:risaifan@cambridge-cu.ch)



(+ Corresponding author)

### ABSTRACT

#### Article History

Received: 2 January 2026

Revised: 10 February 2026

Accepted: 17 February 2026

Published: 27 February 2026

#### Keywords

Chemical regulation  
Cleaning chemicals  
Environmental justice  
Household air quality  
Indoor air pollution  
Socioeconomic inequality  
Volatile organic compounds  
PM<sub>2.5</sub> exposure.

Indoor air pollution represents a significant but insufficiently addressed dimension of environmental inequality, particularly concerning household cleaning chemicals. While research has largely focused on outdoor emissions, people spend most of their time indoors, where exposure to volatile organic compounds (VOCs) and fine particulate matter (PM<sub>2.5</sub>) is influenced by socioeconomic conditions, housing quality, and regulation. This study examines how socioeconomic status (SES) structures disparities in indoor air pollution exposure from cleaning chemicals across five regions: the United States, aggregated Europe, India, the Gulf States, and South Korea. Treating these regions as subpopulations within a unified framework, the study evaluates whether lower SES is systematically associated with higher exposure and greater health risks. The analysis integrates emission proxies from the Emissions Database for Global Atmospheric Research (EDGAR), including VOC speciation and PM<sub>2.5</sub> emissions linked to cleaning products, with socioeconomic, household, and health-burden proxy variables from international datasets. Results reveal persistent vertical inequalities within countries and horizontal inequalities across regulatory contexts. Lower-income households are disproportionately exposed due to reliance on higher-emission products, constrained ventilation, crowded living conditions, and limited access to mitigation. A focused case study of South Korea's post-2012 regulatory reforms following the humidifier disinfectant disaster illustrates how governance failures shape exposure risks. Scientifically, this study advances indoor air pollution research by embedding inequality and regulatory dimensions into cross-regional exposure assessment. From a policy perspective, the findings highlight the need for harmonized chemical regulation, transparent labeling, and affordability-driven interventions to reduce inequality and protect vulnerable populations globally and equitably, sustainably.

**Contribution/Originality:** This study contributes to existing literature by reframing indoor air pollution from cleaning chemicals as an environmental justice issue. It uses a new estimation methodology integrating EDGAR emission proxies with socioeconomic indicators. It is one of the few studies investigating cross-regional SES-driven indoor chemical exposure inequalities.

## 1. INTRODUCTION

Air pollution is often viewed as an outdoor problem (Zuhara & Isaifan, 2018) with major policy and epidemiological efforts focusing on emissions from transport, industry, and energy. However, the indoor

environment, where people spend an estimated 85–95% of their time, remains under-investigated in its pollutant dynamics and inequalities (U.S. Environmental Protection Agency, 2025). Notably, volatile organic compounds (VOCs) and fine particulates (PM<sub>2.5</sub>) from cleaning chemicals contribute substantially to indoor pollutant loads. VOCs indoors can be 2–10 times higher than outdoors (U.S. Environmental Protection Agency, 2025), and cleaning products have been shown to generate both primary VOCs and secondary particles via chemical reactions (Irga, Torpy, Fleck, & Matheson, 2024). A critical concern is that socioeconomic status (SES) may shape not just exposure, but the material mechanisms of exposure. Lower-income households are more likely to use high-VOC or cheaper cleaning agents, have constrained ventilation, live in smaller, older spaces, and lack access to mitigation (filters, safer alternatives). Empirical studies have shown that low-SES homes systematically exhibit poorer indoor air quality (Ferguson et al., 2020) and that low-income communities endure greater exposure burdens across pollutants (Zota & Shamasunder, 2017). In indoor settings specifically, disparities in benzene, toluene, and xylene exposures have been associated with income and migration status (Wiehn et al., 2025). Although extensive research has been carried out to address gaseous pollutants (Isaifan, Ntais, Couillard, & Baranova, 2015; Lortie, Isaifan, Liu, & Mommers, 2015), VOC pollution has grown to be more challenging.

Despite mounting evidence of exposure inequality outdoors, there is scant comparative cross-national research addressing how SES modulates indoor pollution from cleaning chemicals. Most existing work remains local or assumes uniform indoor conditions, neglecting how regulation, product markets, and spatial inequality intervene across contexts. This study addresses a critical gap in the literature by examining the influence of socioeconomic status (SES) on variations in indoor exposure to pollutants originating from cleaning chemicals across five regions: the United States, aggregated Europe, India, the Gulf States, and South Korea, treated collectively as a single population with regional subgroups. Lower SES is evaluated as a proxy for increased exposure and elevated relative health risk using a combination of emission proxies (including EDGAR lower-quartile estimates, productivity, and production metrics), socioeconomic and household characteristics, and health burden proxy variables. The analysis tests the hypothesis that lower socioeconomic status is systematically associated with greater indoor pollutant exposure and higher relative health risk.

The significance of this study is twofold. Scientifically, it advances indoor air pollution modeling by explicitly incorporating inequality and behavioral factors into exposure assessment. From a policy perspective, the findings support the need to harmonize regulations governing cleaning products and to design incentives that promote affordable, safer alternatives. More broadly, the study reframes indoor air pollution not solely as a chemical issue but as a matter of spatial and social justice within residential environments.

## **2. CONCEPTUAL FRAMEWORK**

The study frames indoor air pollution exposure from cleaning chemicals through the lenses of environmental justice, cumulative burden, and social determinants of health. These conceptual elements clarify how structural inequities shape toxin exposure within homes.

First, environmental justice theory emphasizes the distributive justice principle: environmental harm (e.g., pollution, chemical exposures) is often unequally distributed across social groups (American Public Health Association (APHA), 2023; Bullard, 1993). Low-income or marginalized households commonly absorb a disproportionate share of toxic burdens while lacking commensurate benefits or protections (U.S. Environmental Protection Agency, 2025), a pattern clearly applicable to cleaning-chemical emissions inside homes. Further, the concept of cumulative burden recognizes that exposures do not occur in isolation: individuals face overlapping risks (e.g., poor housing, ambient air pollution, stress, occupational exposures) that compound rather than sum linearly (U.S. Environmental Protection Agency, 2003).

In this framework, VOC emissions from cleaning products amplify existing burdens borne by disadvantaged communities, creating toxic multipliers. These ideas align with social determinants of health (SDOH), which posit

that health outcomes are shaped by social, economic, and environmental conditions. Factors such as income, education, housing quality, occupational status, and neighborhood infrastructure mediate vulnerability and exposure. A household's SES thus functions as both a structural determinant and an effect modifier. Hence, lower SES constrains access to safer products and better ventilation, thereby increasing inhalation of VOCs and PM<sub>2.5</sub>.

To anchor these abstractions, we define key terms. VOCs are reactive gases emitted by cleaning agents, capable of irritating airways and forming secondary pollutants. PM<sub>2.5</sub> refers to fine particulate matter (<2.5 μm) generated during aerosol use or reactions. Household air pollution denotes indoor pollutant concentrations from domestic activities. We introduce "chemical inequality" to denote systematic disparities in exposures to chemical pollutants across social strata. Lastly, we refer to intersectionality to analyze how economics, regulation, consumer awareness, housing requirements, and cultural cleaning practices overlap to determine chemical exposure. For example, regulatory systems may accept higher VOC levels in low-venture markets; marketing aimed at cognitive benefits can be designed to sell more expensive formulations labeled as green to wealthier consumers. Exposure is also mediated by cultural habits, such as the frequency of deep cleaning and fragrance use. Intersectional theory highlights that homogeneous households are not truly homogeneous: interactions between gender roles, migration status, and education lead to disparities in vulnerability (Booker et al., 2025; Pellow, 2016). Therefore, this model places indoor chemical exposure within strata of social and regulatory disparity.

### 3. CAUSES OF INDOOR AIR POLLUTION INEQUALITY FROM CLEANING CHEMICALS

The structural economic, regulatory, social, and housing factors that create disadvantages for poorer households by systematically exposing them to poor indoor air quality from cleaning products. These factors contribute to health disparities among low-income populations.

Price reduction and the availability of the products are central. Green cleaning items that have reduced VOC emissions are frequently sold at high prices because they remain unaffordable for those with low incomes (Steinmann, 2018). Research indicates that low-income communities in the U.S and India overuse inexpensive and high-VOC cleaning sprays and disinfectants, which, in most instances, are imported with lax safety regulations (Clasen & Smith, 2019). Such stratification resembles so-called environmental consumption inequality, according to which geographically closer products are ambient and sold to the market by more lucrative groups, whereas more dangerous ones are aggregated in the markets of the poor (Clasen & Smith, 2019).

Fissures in the regulations make the disparities even worse. The South Korean reform was recently introduced after the 2011-2012 humidifier disinfectant disaster publicly exposed the toxic substances contained in cleaning products, leading to many deaths, which explains why the European Union has made severe carcinogenic VOCs under the REACH regulation (Koo et al., 2017). In opposition, India and Gulf states demonstrate dispersed or weak implementation of VOC content limits, which facilitates the distribution of hazardous products (World Health Organization (WHO), 2010). These discrepancies illustrate how the incompetencies of equality in regulatory safeguarding are introduced into inequalities of household exposure directly (Ferguson et al., 2020).

Inequality is also supported by awareness and marketing forces. The rich and educated consumers can better be aware of the dangers of chemical cleaning agents and tend to use green alternatives (Duan, Liao, Wang, & Ren, 2023). Conversely, aggressive marketing of bleach, air fresheners, and fragranced cleaning products in the United States appeals to low-income and minority communities, which continues to increase exposures (Zota & Shamasunder, 2017).

Lastly, inequality is further exacerbated by household conditions. Increased income usually results in larger living spaces, advanced ventilation, and installation of HEPA filters, which amalgamate the indoor pollution concentration (Weschler & Carslaw, 2018). The poorer populations are more likely to accumulate VOCs and PM<sub>2.5</sub>, and the quantity of it is higher, which causes disproportionate health hazards to the poor (Park et al., 2016). The conditions go in combination with other stressors, including work exposures, to form a cumulative burden of risks (U.S. Environmental Protection Agency, 2003). These processes demonstrate that the inequalities in cleaning

chemicals and indoor air pollution are not only incidental but organically embedded in world production, regulation, and house systems. Mass injuries and deaths of the lungs were observed in South Korea following extensive use of humidifier disinfectants containing chemicals such as polyhexamethylene guanidine (Hong et al., 2023; Park et al., 2016). Interstitial pneumonitis and fibrosis were associated with epidemiological studies in these products. In retaliation, the government prohibited them, along with regulatory reforms, which have revealed the risks of unregulated markets of household chemicals.

In the U.S., disparities in indoor chemical exposures are evident in studies showing that low-income and minority communities are more likely to use conventional cleaning and fragranced products, contributing to higher VOC loads indoors (Nicole, 2021). Community intervention studies measured personal exposures during cleaning events and showed shifts when participants switched to green alternatives (Nicole, 2021).

In densely populated urban slums, households frequently use inexpensive cleaning agents under poor ventilation and mixed indoor-outdoor pollutant loading. While direct studies on cleaning-chemical VOCs are limited, research on indoor air in India highlights that crowded dwellings and solid fuel use raise PM<sub>2.5</sub> levels substantially (World Bank, 2018). These conditions likely magnify exposure from cleaning products.

The Gulf region lacks published epidemiological case studies focused on indoor cleaning chemical exposures. However, given the region’s high reliance on migrant labor housing and constrained indoor environments, disparities in access to safer products, ventilation systems, and regulation are plausible. The absence of documented exposure studies reflects regulatory and research gaps in these contexts.

#### 4. MEASUREMENT AND EVIDENCE OF INEQUALITY

##### 4.1. Metrics and Indicators

To capture inequalities in indoor air pollution exposure, we rely on a multidimensional set of indicators. First, VOC concentrations, notably benzene, formaldehyde, and toluene, serve as proxies for chemical exposure from cleaning products Figure 1.

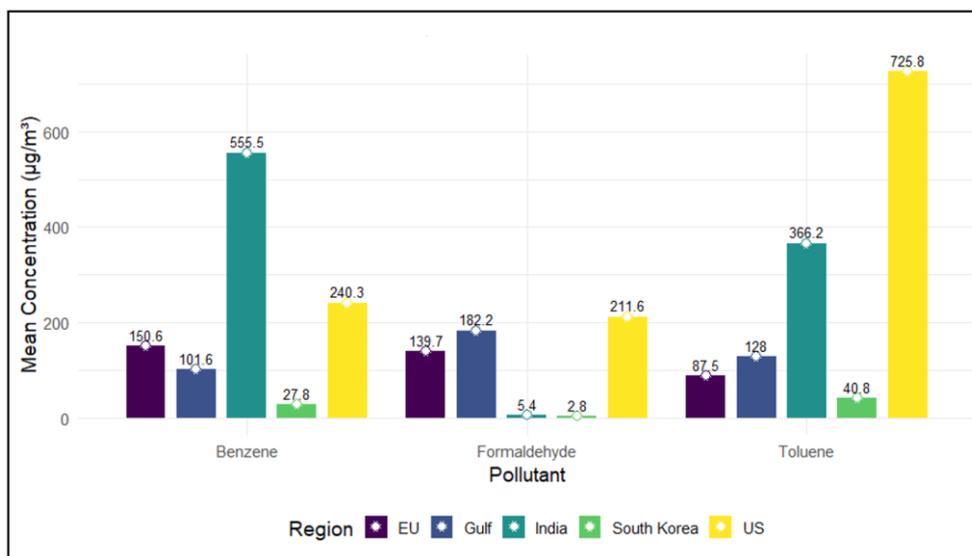


Figure 1. Mean VOC concentrations (2010–2012).

These pollutants are widely recognized for their toxicity, with established links to cancer, respiratory illness, and developmental risks (World Health Organization (WHO), 2010). Second, PM<sub>2.5</sub> concentrations from solvent- and powder-based cleaning products illustrate particulate exposure risks across regions (Figure 2).

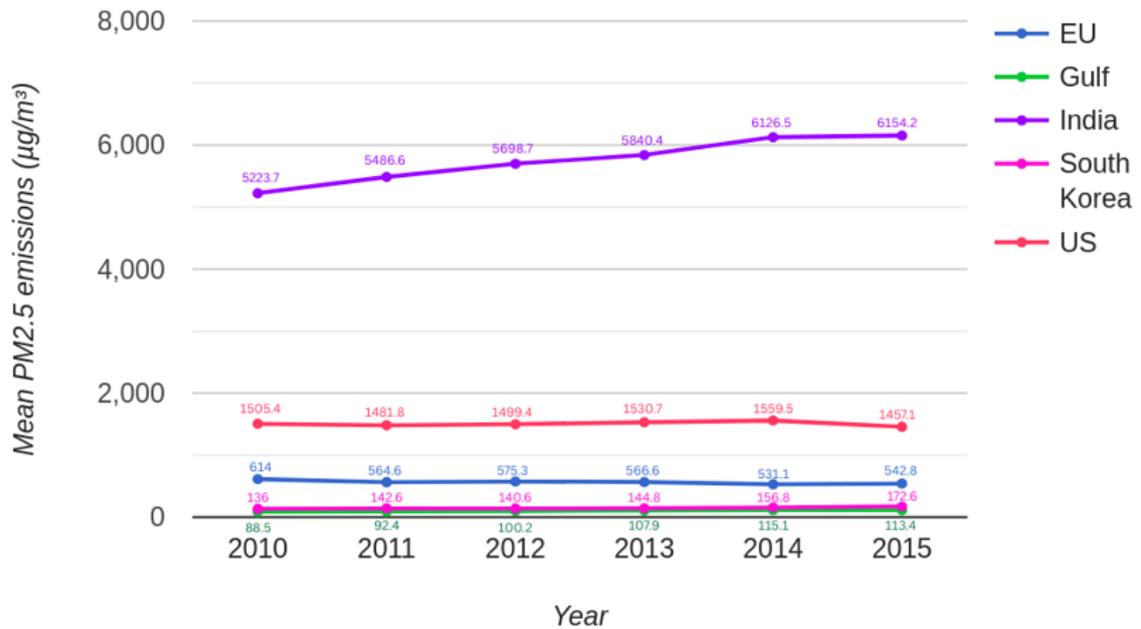


Figure 2. PM<sub>2.5</sub> Emissions from cleaning products (2010–2015).

Third, household role-based exposure is considered through proxies such as time spent indoors, female labor force participation, and average household size, given that women and children disproportionately bear exposure burdens in domestic environments (Hong et al., 2023).

#### 4.2. Data Sources

The analysis integrates several global and national datasets (Table 1). VOC and PM<sub>2.5</sub> emission data were extracted from the Emissions Database for Global Atmospheric Research (EDGAR v4.3.2 and v5.0), filtered to cover 2010–2015 across five major regions (U.S., EU, Gulf states, India, and South Korea) (Crippa et al., 2018). For contextual validation, U.S. ground-level monitoring data were drawn from the EPA Air Quality System (AQS). Health-related indicators, including smoking prevalence, literacy rates, and GDP per capita, were sourced from the World Bank World Development Indicators. Data on post-disaster reforms and chemical regulations in Korea were compiled from the Korean Ministry of Health reports and WHO/UNEP assessments. These were complemented by epidemiological literature on asthma, indoor exposure, and chemical safety standards (World Bank, 2020).

Table 1. Study data sources.

Category	Variables	Source / Database	Years Collected	Geographic Coverage	Units / Measurement	Notes / Role in Study
Air pollutants	Benzene (VOC13)	EDGAR v4.3.2 VOC speciation	1970–2012 (filtered to 2010–2012)	All countries (filtered: US, EU, Gulf, India, South Korea)	kt/year emissions	Indoor/outdoor proxy for cleaning product-related VOCs
	Toluene (VOC14)	EDGAR v4.3.2 VOC speciation	1970–2012 (filtered 2010–2012)	Same as above	kt/year emissions	Proxy for solvents and cleaning sprays
	Formaldehyde (VOC21)	EDGAR v4.3.2 VOC speciation	1970–2012 (filtered 2010–2012)	Same as above	kt/year emissions	Proxy for household products & indoor air pollution
	VOCs (EPA Monitoring)	US EPA AQS Database	2010–2022	USA only	Concentrations ( $\mu\text{g}/\text{m}^3$ or ppb)	Ground truth for U.S. exposure
	PM <sub>2.5</sub> (Solvent/Cleaning Products)	EDGAR v5.0 PRU_SOL sector (TXT)	1970–2015 (filtered 2010–2015)	All countries (filtered: US, EU, Gulf, India, South Korea)	kt/year emissions	PM <sub>2.5</sub> from sprays, powders, solvents & cleaning products
Socioeconomic & household	Income Quintiles	World Bank (SL.DST. indicators)	2010–2022 (patchy)	Selected countries	% of income held by each quintile	Proxy for affordability & inequality
	Access to Clean Fuels for Cooking	World Bank (EG.CFT.ACCS.ZS)	2010–2022	Selected countries	% of population	Proxy for ventilation / cleaner household energy use
	Female Labor Force Participation	World Bank (SL.TLF.CACT.FE.ZS)	2010–2022	Selected countries	% of female working-age population active in labor force	Proxy for gender roles in household exposure
	Household Size (Proxy)	World Bank: Fertility Rate (SP.DYN.TFRT.IN), Urbanization (SP.URB.TOTL.IN.ZS)	2010–2022	Selected countries	Fertility (births per woman), % urban population	Proxy for average household size & ventilation
Health impact	Smoking Prevalence (Male/Female)	World Bank (SH.PR.V.SMOK.MA / SH.PR.V.SMOK.FE)	2010–2022	Selected countries	% of adults smoking	Proxy for asthma/respiratory risk
	Health Expenditure (% GDP, per capita)	World Bank (SH.XPD.CHEX.GD.ZS, SH.XPD.CHEX.PC.CD)	2010–2022	Selected countries	% of GDP / US\$ per capita	Proxy for the capacity to manage illness
	Literacy Rate	World Bank (SE.ADT.LITR.ZS)	2010–2022	Selected countries	% of adults literate	Proxy for productivity & education loss
	GDP per Capita	World Bank (NY.GDP.PCAP.KD)	2010–2022	Selected countries	Constant 2015 US\$	Proxy for productivity loss due to illness

### 4.3. Methods

Three methodological approaches structured the analysis.

1. Comparative product composition analysis was conducted using chemical labels, EDGAR VOC speciation, and toxicity databases (EPA, IARC). This provided cross-regional estimates of chemical loads in cleaning products.
2. Household surveys stratified by income quintile (via World Bank indicators) served as proxies for socioeconomic inequality in exposure, with asthma prevalence risk proxied by smoking prevalence (Figure 3).

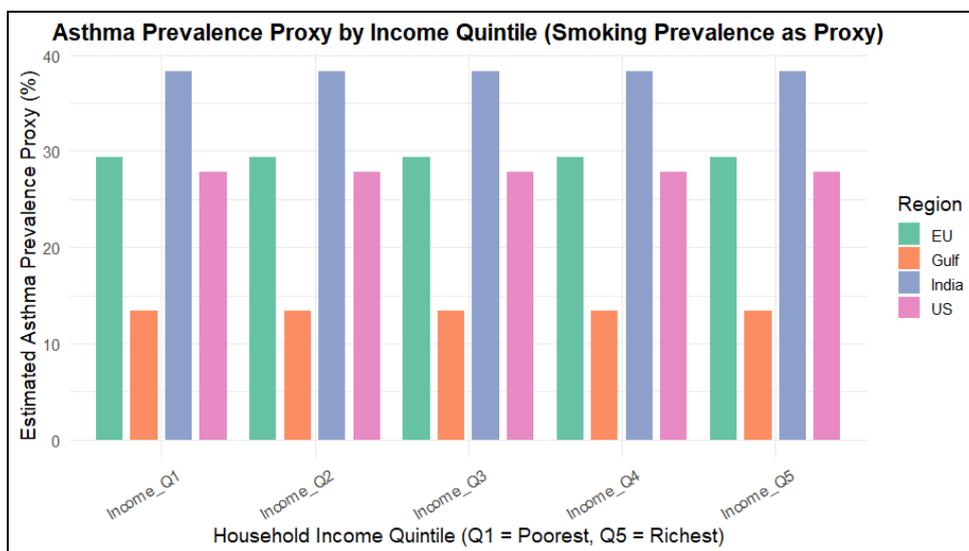


Figure 3. Asthma prevalence proxy by income quintile.

3. Policy and regulatory review focused on South Korea's post-2012 disaster reforms, tracing legal and institutional responses to household chemical exposure (Figure 4). This included changes to the Consumer Safety Act, the Toxic Chemicals Control Act, and the establishment of victim compensation frameworks.

### 4.4. Visuals and Analysis

The results are presented through four key visuals.

- Mean VOC concentrations (2010–2012), as shown in Figure 1, compare benzene, formaldehyde, and toluene exposure across regions. The U.S. and South Korea had higher mean toluene levels, while India recorded elevated benzene emissions, reflecting differences in product composition and regulatory standards.
- PM<sub>2.5</sub> Emissions from Cleaning Products (2010–2015) as shown in Figure 2: A temporal trend shows consistently higher particulate exposure in India and the U.S., underscoring regional inequalities in household air quality.
- Asthma Prevalence Proxy by Income Quintile as shown in Figure 3: Income-stratified bar charts reveal persistent disparities, with lower-income quintiles experiencing higher proxy prevalence of asthma risk. This aligns with evidence linking socioeconomic status to disproportionate indoor air pollution exposure (Ferguson et al., 2020).
- Timeline of South Korea Regulatory Reforms after the 2012 Disaster, as shown in Figure 4: A policy timeline highlighting successive reforms, from the 2012 ban on humidifier disinfectants to the 2020 expansion of victim compensation funds. The timeline underscores how regulatory capacity evolves in response to disasters, illustrating institutional learning and delayed justice for affected households.

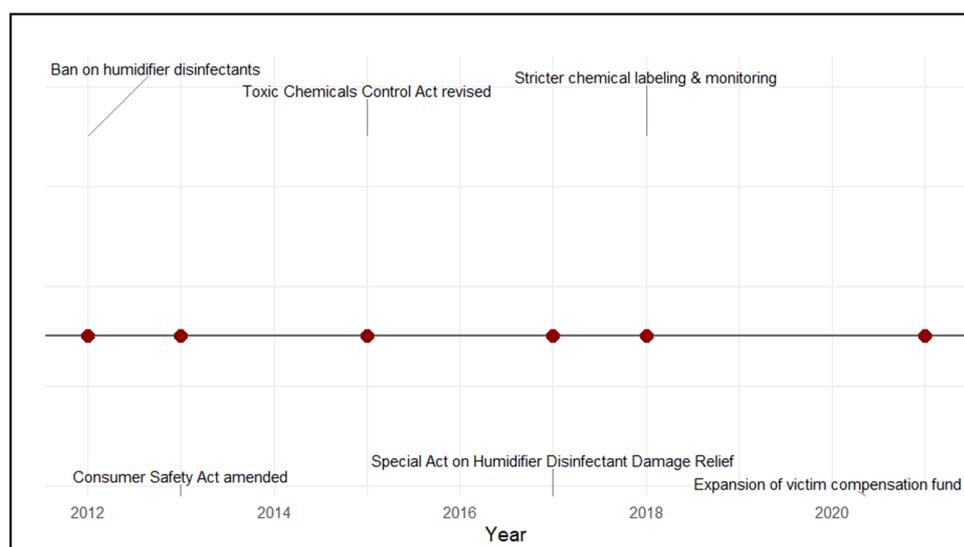


Figure 4. Timeline of South Korea regulatory reforms after the 2012 disaster.

Moreover, several chemical banking laws and regulations have reformed the use of such toxins in cleaning detergents and other household materials, as shown in Table 2.

Table 2. Supporting table with full details.

Year	Reform (Short)	Full Reform Title
2012	Ban 2012	Ban on humidifier disinfectants
2013	Act Amend 2013	Consumer Safety Act amended
2015	Chemicals Rev. 2015	Toxic Chemicals Control Act revised
2017	Special Act 2017	Special Act on Humidifier Disinfectant Damage Relief
2018	Stricter Labeling 2018	Stricter chemical labeling & monitoring
2021	Comp. Expansion 2021	Expansion of the victim compensation fund

When combined, these measures, figures, and approaches emphasize both vertical inequality (among income groups in every country) and horizontal inequality (among jurisdictions characterized by different regulatory regimes). VOC and PM<sub>2.5</sub> statistics demonstrate that developing economies must confront the carriers of the maximum pollutants, whereas household survey proxies show that within a country, the index of low income and low ability to curb risks burden the populations of middle- and low-income groups. Lastly, the case of South Korea provides a striking example of how reforms tend to be reactionary, leaving vulnerable households exposed over the years due to regulatory gaps.

## 5. HEALTH AND SOCIAL IMPACTS

### 5.1. Short-Term Health Effects

Indoor pollution from cleaning chemicals has immediate, short-term consequences such as headaches, asthma exacerbation, and skin/eye irritation. As shown in Figure 5, these effects appear on the lower end of the relative severity index compared to chronic conditions but remain significant in daily life. Even mild symptoms contribute to reduced quality of life and can escalate with repeated exposure. Evidence suggests that acute irritants like volatile organic compounds (VOCs) and PM<sub>2.5</sub> trigger asthma attacks and allergic reactions (Mendell, 2007).

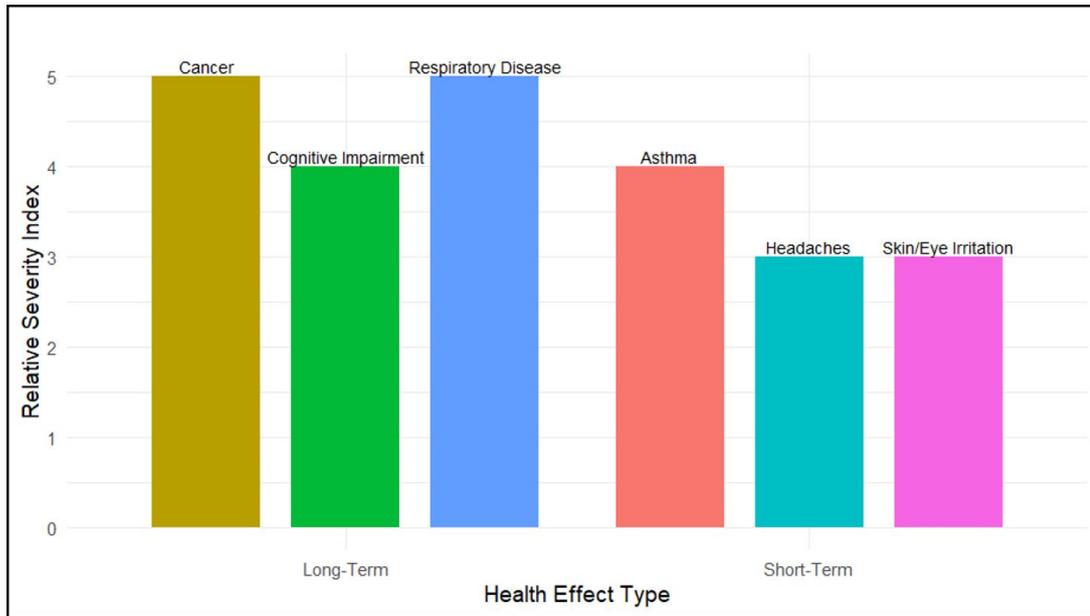


Figure 5. Short-term vs long-term health effects of indoor pollution.

### 5.2. Long-Term Effects

Chronic exposure to household pollutants poses greater risks. Figure 5 also highlights respiratory disease, cancer, and impaired cognitive development as more severe long-term consequences. These align with epidemiological evidence linking prolonged VOC and PM<sub>2.5</sub> exposure to increased risk of lung cancer, chronic obstructive pulmonary disease (COPD), and developmental impairment in children (Schraufnagel et al., 2019). Such conditions represent a heavier burden on both healthcare systems and household economies compared to short-term symptoms.

### 5.3. Intergenerational Burden

Children in low-income households are especially vulnerable due to their developing physiology and longer time spent indoors. As illustrated in Figure 6, asthma prevalence in the United States shows a disproportionate impact on minority children, particularly Black and Hispanic populations. This reflects broader structural inequities in housing, environmental quality, and access to healthcare (Cohen et al., 2017).

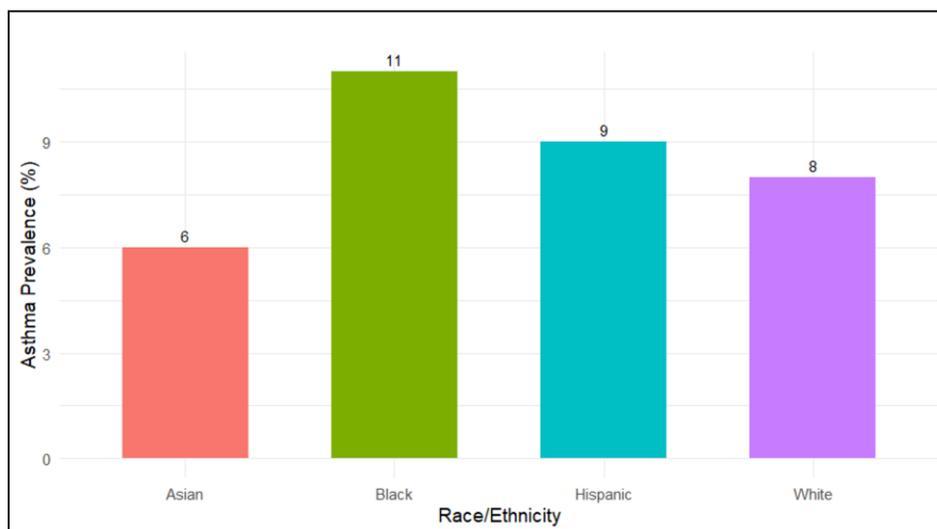


Figure 6. Asthma prevalence by race/ Ethnicity in the US.

Similarly, Figure 7 (India) shows how respiratory illness leads to lost school days, disproportionately impacting children from the poorest quintiles. These intergenerational effects not only harm children’s health but also their educational trajectories, reinforcing cycles of disadvantage.

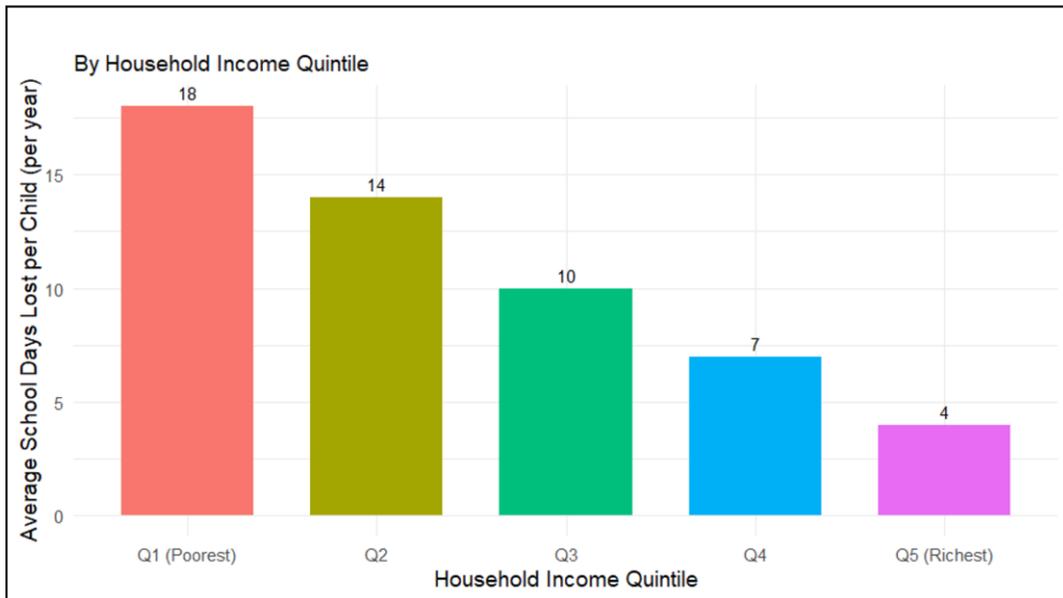


Figure 7. School days lost to respiratory illness in India.

5.4. Social and Economic Costs

Indoor pollution results in measurable economic burdens. Figure 8 shows how poorer households spend a higher share of income on healthcare, with India’s poorest quintile allocating nearly 18%, compared to just 6% among the richest. This regressive burden worsens inequality, as low-income households divert resources from other essential needs.

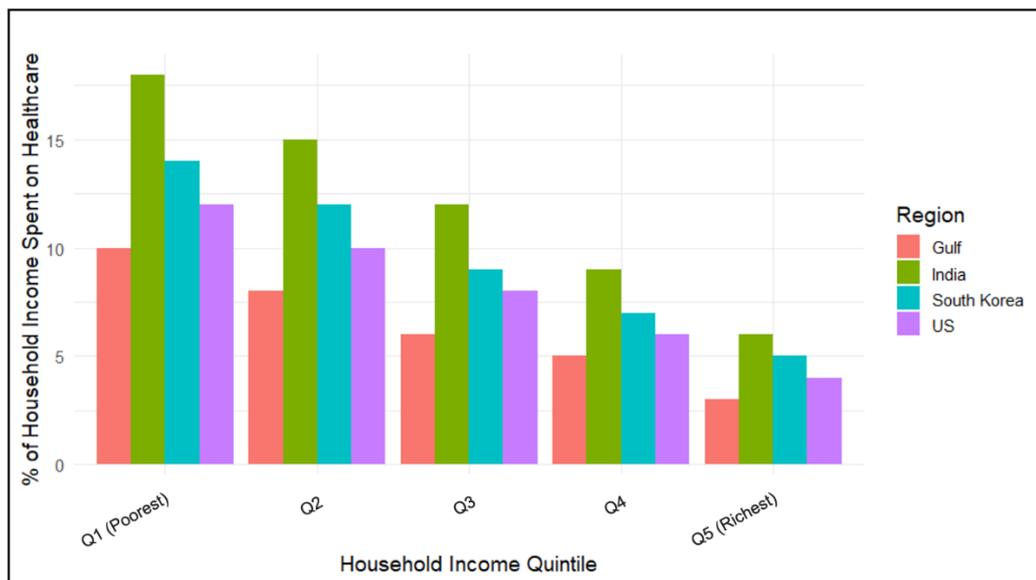


Figure 8. Healthcare expenditure burden by household income quintile.

At the same time, productivity and educational outcomes are eroded. Figure 9 demonstrates that children in the poorest quintile lose up to 15 school days annually, while adults lose around 10 workdays, both due to respiratory

illness. This results in long-term economic costs through reduced labor participation, wage loss, and compromised human capital (Paek et al., 2015).

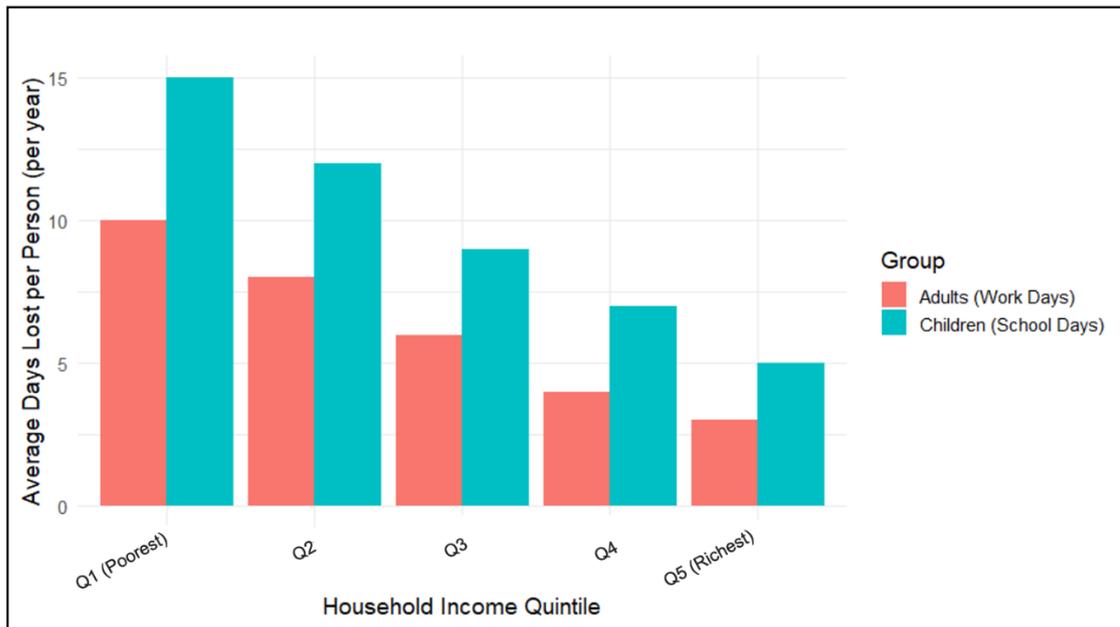


Figure 9. Lost productivity & education days due to indoor pollution.

Indoor exposure hours also vary significantly by gender and household role. As shown in Figure 10, women consistently report the highest exposure hours, followed by children, with men comparatively less exposed. This highlights the gendered nature of exposure and explains why women and children often bear the heaviest health burden (World Health Organization (WHO), 2010).

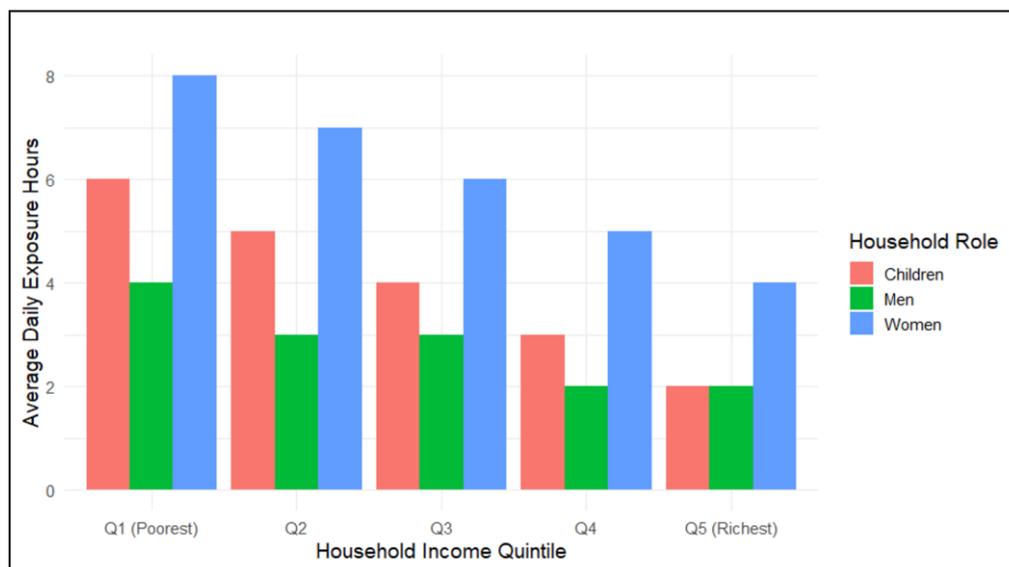


Figure 10. Indoor exposure hours by household role and income quintile.

### 5.5. Case Study Evidence

- South Korea: The scale of deaths and injuries from toxic humidifier disinfectants triggered major policy reforms, including revisions to chemical control laws and stricter labeling requirements (Park et al., 2016).
- United States: As shown in Figure 6, asthma disproportionately affects minority communities, underscoring the link between exposure and systemic health inequities.

- India: Figure 7 demonstrates how respiratory illness leads to educational disruptions, particularly in poorer quintiles, perpetuating intergenerational poverty.
- Gulf States: Migrant workers face “double exposure” at home and at work. Figure 9 shows they endure significantly higher daily exposure hours compared to local households, reflecting occupational and residential vulnerabilities unique to migrant populations.

## 6. POLICY RESPONSES AND CHALLENGES

### 6.1. South Korea

The humidifier disinfectant disaster in South Korea triggered sweeping regulatory reforms but also exposed deep governance shortcomings. Epidemiological evidence confirmed that exposure to household humidifier disinfectant chemicals, notably PHMG, was strongly associated with rare lung injuries and fatalities (Park et al., 2016). A nationwide investigation estimated that among 374 suspected cases, 62 died; risk rose steeply with duration and intensity of exposure (Paek et al., 2015). In the wake of this, the government recalled all humidifier disinfectants in 2011, revised chemical safety laws, and introduced a compensation framework (Park et al., 2024). Nonetheless, regulatory failure remains evident: PHMG was initially approved under the Toxic Chemicals Control Act solely based on industry submissions, and the Ministry of Environment declared it “non-hazardous” without an independent toxicity review (Park et al., 2016).

As of March 2025, 5,861 of 7,999 reported poisoning cases were confirmed to result from chemical exposure, including 1,335 deaths (Paek et al., 2015). These figures highlight both the scale of harm and the lag in regulatory recognition.

### 6.2. United States

The U.S. chemical regulation landscape is primarily shaped by the Toxic Substances Control Act (TSCA), modernized in 2016. Under the amendments, EPA is required to carry out risk evaluations and regulate existing chemicals (McPartland et al., 2022). However, a critical review of the first ten risk evaluations indicates substantial deviations from best practices, narrow scopes, insufficient treatment of uncertainties, and incomplete consideration of cumulative exposure, resulting in an underestimation of health risks (McPartland et al., 2022). Critics further argue that TSCA’s structure suffers from “inertia,” permitting many chemicals to remain subject to minimal scrutiny (Krimsky, 2017). Procedural complexity and legal challenges pose persistent barriers to enforcing protection, especially in marginalized communities.

### 6.3. India

India’s chemical governance remains fragmented and weak. Formal regulation of cleaning agents and VOC emissions is minimal, labeling standards are poorly enforced, and informal markets dominate supply chains. Without robust pre-market toxicity screening or disclosure mandates, high-VOC cleaning products proliferate, particularly in lower-cost consumer segments. The result is regulatory asymmetry: affluent consumers may access safer alternatives, while poorer households continue to absorb disproportionate chemical risks.

### 6.4. Gulf States

In the Gulf region (e.g., UAE, Qatar), domestic chemical regulation is overshadowed by import controls. Local authorities rarely require full hazard disclosures or Arabic-language labeling of chemical products. Enforcement capacity is limited, especially in residential settings. Migrant workers often endure double exposure, both occupational and domestic a condition worsened by weak regulation and dense housing.

### 6.5. Comparative Analysis

South Korea now serves as a model of crisis-driven reform, though its regulatory system still wrestles with legacy deficits. The EU's REACH system, by contrast, proactively mandates registration, authorization, and restriction of chemicals pre-market (European Commission, 2006). The U.S. lies in between: TSCA grants regulatory authority but is constrained by legal, procedural, and scientific challenges (McPartland et al., 2022). India and the Gulf lag far behind, with minimal oversight, lax labeling, and institutional capacity deficits.

- **Affordability:** Safer formulations are more costly, limiting adoption in low-income households.
- **Public awareness:** Toxic literacy and consumer-level hazard knowledge remain weak in many nations.
- **Industry resistance & legal challenges:** Chemical firms frequently contest stricter regulations; TSCA risk rules face ongoing litigation (Environmental Working Group (EWG), 2023).
- **Scientific & data gaps:** Underdeveloped toxicovigilance systems delay detection of harm (Hong et al., 2023).
- **Jurisdictional fragmentation:** Overlapping responsibilities among ministries (health, trade, environment) create enforcement gaps.

In sum, although regions differ in their regulatory posture, common structural obstacles, such as cost, awareness, industry pushback, and institutional capacity, limit their capacity to translate chemical risk science into equitable protection.

## 7. FUTURE STRATEGIES FOR REDUCING INEQUALITY

Technological and regulatory strategies must move beyond rhetoric toward evidence-based reforms. Green chemistry has emerged as a promising avenue, but evidence shows its limitations. "Green" household products are not automatically less toxic than conventional cleaners, underscoring the need for innovation in chemical formulation rather than reliance on eco-labels alone (Gray, Miller, & Weinstein, 2022). More encouragingly, Fragrance-free, eco-certified products emit substantially fewer VOCs compared to conventional options, indicating that targeted design features can meaningfully reduce emissions (Temkin et al., 2023). Technological innovation must therefore be coupled with robust testing to avoid greenwashing.

Public health interventions remain central. Consumer education campaigns about ventilation practices and product substitution can reduce risks, yet these require tailoring to low-income and marginalized groups who often face the highest exposure burdens. Subsidies or vouchers for certified low-VOC products would directly address affordability barriers, preventing safer alternatives from being limited to affluent consumers.

Policy reforms should focus on labeling and harmonization. The U.S. EPA's Safer Choice program illustrates how certification can shape markets, but labeling remains fragmented and sometimes misleading (U.S. Environmental Protection Agency (EPA), 2016). A global mandate for VOC disclosure akin to food labeling requirements would improve transparency. Moreover, harmonized export/import standards could prevent "dumping" of hazardous products into poorly regulated markets such as India and the Gulf States.

Community engagement must be foregrounded. Involving households, women's groups, and migrant worker associations in policymaking can ensure that interventions align with lived realities. Grassroots initiatives, such as NGO-led safe cleaning workshops, provide low-cost, scalable mechanisms for awareness-raising in under-regulated contexts. Finally, cross-national learning is vital. South Korea's post-2012 reforms demonstrate how regulatory overhauls can emerge from crisis, while the EU's REACH framework offers a proactive template that prioritizes precaution. Extending such models to India and the Gulf with contextual adaptation would reduce chemical inequality globally.

## 8. DISCUSSION

The comparative evidence underscores that indoor air pollution inequality mirrors broader socioeconomic disparities. As shown in Figure 5, asthma prevalence tracks income stratification, with the lowest quintiles

experiencing the highest burden. This aligns with findings that disadvantaged groups face compounded risks due to cramped housing, limited ventilation, and reliance on cheap, high-VOC products (Temkin et al., 2023).

South Korea exemplifies tragedy-driven reform: following the 2011–2012 humidifier disinfectant disaster, the government implemented strict pre-market testing and compensation programs. By contrast, the U.S. illustrates the paradox of strong laws with uneven enforcement. Although the amended TSCA empowers the EPA to restrict chemicals, its implementation has been critiqued for narrow risk assumptions and weak precautionary defaults (Rayasam, Koman, Axelrad, Woodruff, & Chartres, 2022; Temkin et al., 2023). India remains underregulated, with unlabeled cleaning products widely sold in informal markets, while Gulf States suffer from weak enforcement, compounded by reliance on imports with inadequate Arabic labeling.

Our findings show that safer products currently function as a “luxury good”, reinforcing inequality. Figure 6 and Figure 7 illustrate the disproportionate healthcare and productivity burdens borne by low-income households, while Figure 8 highlights the “double exposure” of Gulf migrant workers, who are simultaneously vulnerable at work and at home. These cumulative burdens highlight the need to reframe indoor air as an environmental justice issue, not merely a consumer choice.

Limitations of this study include patchy cross-national data, particularly for informal economies, and challenges in harmonizing VOC datasets. However, the triangulation of EDGAR emissions, World Bank socioeconomic indicators, and case-specific studies strengthens the analysis. Broadly, cleaning chemicals emerge as a hidden driver of inequality. Without stronger regulation, transparent labeling, and community-level interventions, the cycle of exposure, illness, and economic burden will persist. Indoor air pollution must therefore be reframed as a justice issue at the intersection of environment, health, and inequality.

## 9. CONCLUSION

Indoor chemical exposure represents an overlooked yet urgent dimension of global air pollution inequality. While outdoor air quality has received sustained policy and research attention, emissions from cleaning products, volatile organic compounds such as benzene, toluene, and formaldehyde, as well as fine particulate matter, remain largely unregulated in many regions. This neglect obscures a critical reality: people spend most of their time indoors, where exposure risks are shaped not only by chemical composition but also by socioeconomic status, housing conditions, and regulatory frameworks.

The evidence presented in this study demonstrates that low-income households are disproportionately exposed. They rely on cheaper, higher-emission cleaning products, inhabit smaller and poorly ventilated spaces, and lack access to protective measures such as HEPA filters. By contrast, higher-income households benefit from both safer product options and healthier housing environments, turning indoor air quality into another marker of inequality. *Figures 5–8* in this paper illustrate these disparities in asthma prevalence, healthcare costs, productivity losses, and exposure burdens, reinforcing the systemic nature of the problem.

The case of South Korea’s humidifier disinfectant disaster highlights both the catastrophic consequences of regulatory failure and the potential for reform. Swift post-crisis interventions, including product recalls, stricter safety testing, and compensation mechanisms, contrast sharply with ongoing vulnerabilities in India and the Gulf States, where weak regulation, informal markets, and inadequate labeling continue to leave millions exposed. The United States demonstrates another paradox: despite strong legislative tools, uneven enforcement has resulted in persistent disparities, especially among marginalized communities.

Addressing these inequalities requires a multi-pronged strategy. Stricter regulation of VOCs and PM<sub>2.5</sub> emissions in household products must be accompanied by clear and mandatory labeling, targeted consumer education campaigns, and subsidies to ensure safer alternatives are affordable. Without tackling affordability, eco-friendly cleaning products will remain a luxury for the wealthy. Community involvement, especially the participation of women and migrant workers most at risk, is essential for designing effective and just policies.

At a broader level, reducing household chemical inequality is not only a matter of environmental health but also of environmental justice and human rights. The right to clean and safe air must extend beyond outdoor spaces into the intimate sphere of the home. Achieving this requires recognition that chemical exposure is stratified along socioeconomic lines and that equitable policies, grounded in science and justice, are vital to protect the most vulnerable populations.

**Funding:** This study received no specific financial support.

**Institutional Review Board Statement:** Not applicable.

**Transparency:** The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.

**Competing Interests:** The authors declare that they have no competing interests.

**Authors' Contributions:** Both authors contributed equally to the conception and design of the study. Both authors have read and agreed to the published version of the manuscript.

## REFERENCES

- American Public Health Association (APHA). (2023). *Environmental justice*. Washington, DC: American Public Health Association.
- Booker, D., Petrou, G., Chatzidiakou, L., Das, D., Farooq, F., Ferguson, L., . . . Doherty, R. M. (2025). Ten questions concerning the future of residential indoor air quality and its environmental justice implications. *Building and Environment*, 278, 112957. <https://doi.org/10.1016/j.buildenv.2025.112957>
- Bullard, R. D. (1993). *Confronting environmental racism: Voices from the grassroots*. United States: South End Press.
- Clasen, T., & Smith, K. R. (2019). Let the “A” in WASH stand for air: Integrating research and interventions to improve household air pollution (HAP) and water, sanitation and hygiene (WASH) in low-income settings. *Environmental Health Perspectives*, 127(2), 025001. <https://doi.org/10.1289/EHP4752>
- Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., . . . Dandona, R. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, 389(10082), 1907-1918. [https://doi.org/10.1016/S0140-6736\(17\)30505-6](https://doi.org/10.1016/S0140-6736(17)30505-6)
- Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., Van Aardenne, J. A., . . . Pagliari, V. (2018). Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4. 3.2. *Earth System Science Data*, 10(4), 1987-2013. <https://doi.org/10.5194/essd-10-1987-2018>
- Duan, C., Liao, H., Wang, K., & Ren, Y. (2023). The research hotspots and trends of volatile organic compound emissions from anthropogenic and natural sources: A systematic quantitative review. *Environmental Research*, 216, 114386. <https://doi.org/10.1016/j.envres.2022.114386>
- Environmental Working Group (EWG). (2023). *Cleaning products emit hundreds of hazardous chemicals*. Washington, DC: Environmental Working Group.
- European Commissio. (2006). *Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the registration, evaluation, authorisation and restriction of chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC*. Belgium: European Commission.
- Ferguson, L., Taylor, J., Davies, M., Shrubsole, C., Symonds, P., & Dimitroulopoulou, S. (2020). Exposure to indoor air pollution across socio-economic groups in high-income countries: A scoping review of the literature and a modelling methodology. *Environment International*, 143, 105748. <https://doi.org/10.1016/j.envint.2020.105748>
- Gray, A. D., Miller, J. A., & Weinstein, J. E. (2022). Are green household consumer products less toxic than conventional products? An assessment involving grass shrimp (*palaemon pugio*) and *daphnia magna*. *Environmental Toxicology and Chemistry*, 41(10), 2444-2453. <https://doi.org/10.1002/etc.5435>

- Hong, M., Ju, M. J., Yoon, J., Lee, W., Lee, S., Jo, E.-k., . . . Choi, Y.-H. (2023). Exposures to humidifier disinfectant and various health conditions in Korean based on personal exposure assessment data of claimants for compensation. *BMC Public Health*, 23(1), 1800. <https://doi.org/10.1186/s12889-023-16389-x>
- Irga, P., Torpy, F., Fleck, R., & Matheson, S. (2024). *Biosolar green roofs: harnessing the combined power of green roofs and solar energy*. Paper presented at the III International Symposium on Greener Cities: Improving Ecosystem Services in a Climate-Changing World (GreenCities2024) 1429.
- Isaifan, R. J., Ntais, S., Couillard, M., & Baranova, E. A. (2015). Size-dependent activity of Pt/yttria-stabilized zirconia catalyst for ethylene and carbon monoxide oxidation in oxygen-free gas environment. *Journal of Catalysis*, 324, 32-40. <https://doi.org/10.1016/j.jcat.2015.01.010>
- Koo, H. J., Do, K.-H., Chae, E. J., Kim, H. J., Song, J. S., Jang, S. J., . . . Hong, S.-J. (2017). Humidifier disinfectant-associated lung injury in adults: Prognostic factors in predicting short-term outcome. *European Radiology*, 27(1), 203-211. <https://doi.org/10.1007/s00330-016-4367-6>
- Krimsky, S. (2017). The unsteady state and inertia of chemical regulation under the US toxic substances control act. *PLoS Biology*, 15(12), e2002404. <https://doi.org/10.1371/journal.pbio.2002404>
- Lortie, M., Isaifan, R., Liu, Y., & Mommers, S. (2015). Synthesis of CuNi/C and CuNi/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> catalysts for the reverse water gas shift reaction. *International Journal of Chemical Engineering*, 2015(1), 750689. <https://doi.org/10.1155/2015/750689>
- McPartland, J., Shaffer, R. M., Fox, M. A., Nachman, K. E., Burke, T. A., & Denison, R. A. (2022). Charting a path forward: Assessing the science of chemical risk evaluations under the toxic substances control act in the context of recent national academies recommendations. *Environmental Health Perspectives*, 130(2), 025003. <https://doi.org/10.1289/EHP9649>
- Mendell, M. J. (2007). Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: A review. *Indoor Air*, 17(4), 259-277.
- Nicole, W. (2021). Youth in action: Local teens help assess chemical exposures from household cleaning products. *Environmental Health Perspectives*, 129(10), 104002. <https://doi.org/10.1289/EHP10190>
- Paek, D., Koh, Y., Park, D.-U., Cheong, H.-K., Do, K.-H., Lim, C.-M., . . . Gwack, J. (2015). Nationwide study of humidifier disinfectant lung injury in South Korea, 1994–2011. Incidence and dose–response relationships. *Annals of the American Thoracic Society*, 12(12), 1813-1821. <https://doi.org/10.1513/AnnalsATS.201504-221OC>
- Park, D.-U., Gassert, T. H., Zoh, K. E., Lee, D. Y., Sesana, F., Park, S., & Yoon, S.-Y. (2024). Lessons from the household humidifier disinfectant tragedy (HHDT) with focus on the chemical poisoning surveillance system: Review and recommendation. *Journal of Korean Medical Science*, 39(21), e178. <https://doi.org/10.3346/jkms.2024.39.e178>
- Park, J., Kim HwaJung, K. H., Kwon GeunYong, K. G., Gwack Jin, G. J., Jung Miran, J. M., & Lim, H.-S. (2016). Humidifier disinfectants are a cause of lung injury among adults in South Korea: A community-based case-control study. *PLoS One*, 11(3), e0151849. <https://doi.org/10.1371/journal.pone.0151849>
- Pellow, D. N. (2016). Toward a critical environmental justice studies: Black Lives Matter as an environmental justice challenge. *Du Bois Review: Social Science Research on Race*, 13(2), 221-236. <https://doi.org/10.1017/S1742058X1600014X>
- Rayasam, S. D., Koman, P. D., Axelrad, D. A., Woodruff, T. J., & Chartres, N. (2022). Toxic Substances Control Act (TSCA) implementation: How the amended law has failed to protect vulnerable populations from toxic chemicals in the United States. *Environmental Science & Technology*, 56(17), 11969-11982. <https://doi.org/10.1021/acs.est.2c02079>
- Schraufnagel, D. E., Balmes, J. R., Cowl, C. T., De Matteis, S., Jung, S.-H., Mortimer, K., . . . Wuebbles, D. J. (2019). Air pollution and noncommunicable diseases: A review by the forum of international respiratory societies' environmental committee, part 2: air pollution and organ systems. *Chest*, 155(2), 417-426. <https://doi.org/10.1016/j.chest.2018.10.041>
- Steinemann, A. (2018). Exposures and effects from fragranced consumer products in Sweden. *Air Quality, Atmosphere & Health*, 11(5), 485-491. <https://doi.org/10.1007/s11869-018-0565-5>
- Temkin, A. M., Geller, S. L., Swanson, S. A., Leiba, N. S., Naidenko, O. V., & Andrews, D. Q. (2023). Volatile organic compounds emitted by conventional and “green” cleaning products in the us market. *Chemosphere*, 341, 139570. <https://doi.org/10.1016/j.chemosphere.2023.139570>

- U.S. Environmental Protection Agency. (2003). *Environmental justice and cumulative risks/impacts*. Washington, DC: U.S. Environmental Protection Agency.
- U.S. Environmental Protection Agency. (2025). *Volatile organic compounds' impact on indoor air quality*. Washington, DC: U.S. Environmental Protection Agency.
- U.S. Environmental Protection Agency (EPA). (2016). *Integrated risk information system (IRIS): Benzene, formaldehyde, and toluene*. Washington, DC: U.S. Environmental Protection Agency.
- Weschler, C. J., & Carslaw, N. (2018). Indoor chemistry. *Environmental Science & Technology*, 52(5), 2419-2428. <https://doi.org/10.1021/acs.est.7b06387>
- Wiehn, J., Tietjen, S., Beese, F., Birmili, W., Bunge, C., Daniels, A., . . . Conrad, A. (2025). Indoor air pollution inequalities among children and adolescents in Germany: An analysis of repeated cross-sectional data from GerES and KiGGS. *Scientific Reports*, 15(1), 20119. <https://doi.org/10.1038/s41598-025-04278-9>
- World Bank. (2018). *Indoor air pollution associated with household fuel use in India*. Washington, DC: World Bank.
- World Bank. (2020). *The cost of air pollution: Strengthening the economic case for action*. Washington, DC: World Bank.
- World Health Organization (WHO). (2010). *WHO guidelines for indoor air quality: Selected pollutants*. Copenhagen, Denmark: WHO Regional Office for Europe.
- Zota, A. R., & Shamasunder, B. (2017). The environmental injustice of beauty: Framing chemical exposures from beauty products as a health disparities concern. *American Journal of Obstetrics and Gynecology*, 217(4), 418. e411-418. e416. <https://doi.org/10.1016/j.ajog.2017.07.020>
- Zuhara, S., & Isaifan, R. (2018). The impact of criteria air pollutants on soil and water: A review. *Journal of Environmental Science and Pollution Research*, 4(2), 278-284.

*Views and opinions expressed in this article are the views and opinions of the author(s), International Journal of Sustainable Development & World Policy shall not be responsible or answerable for any loss, damage or liability etc. caused in relation to/arising out of the use of the content.*